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INSTITUTE OF GEOLOGICAL SCIENCES

British Regional Geology

The South of Scotland

(THIRD EDITION)

EDINBURGH: HER MAJESTY'S STATIONERY OFFICE

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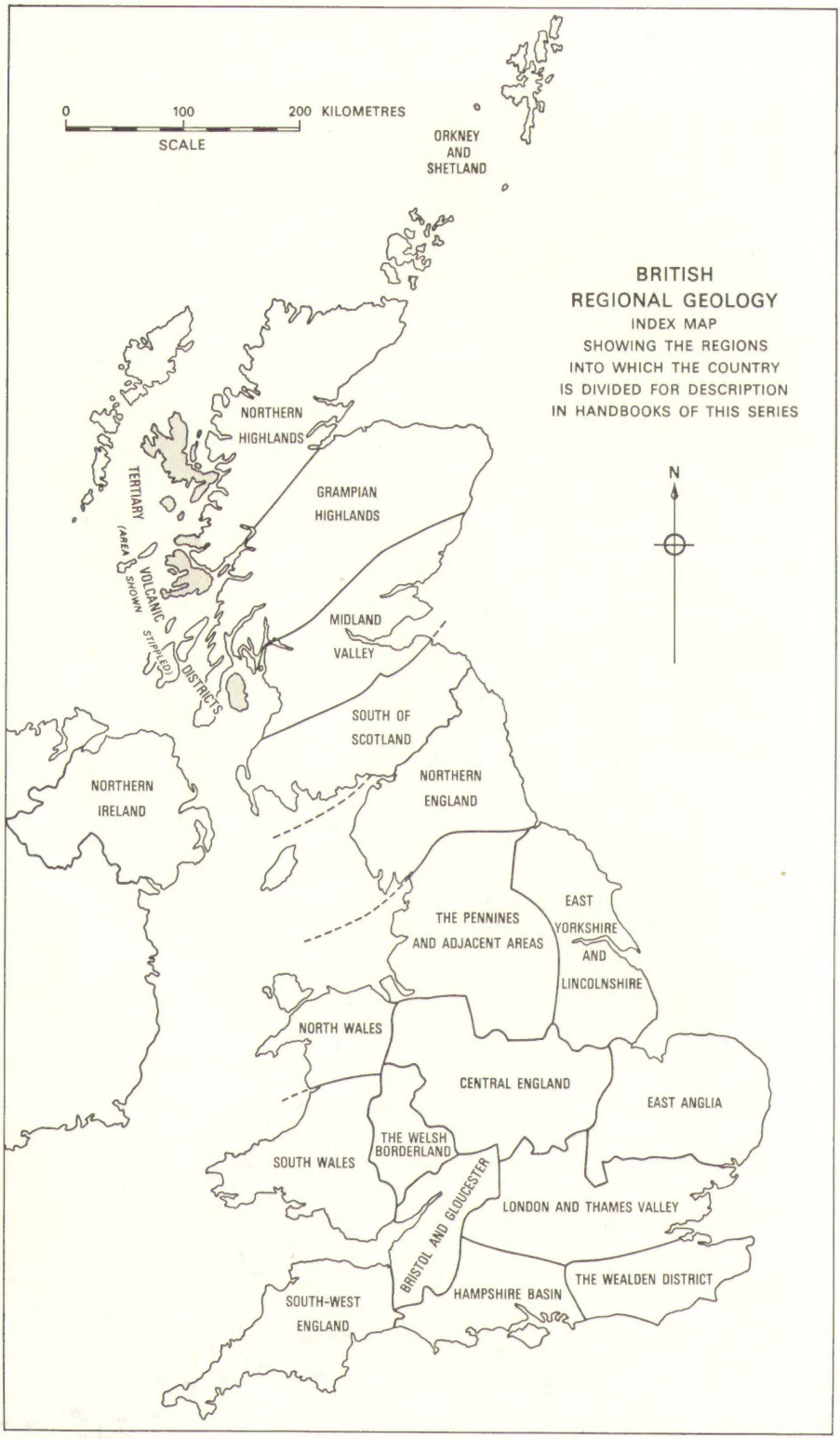
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SCALE
ORKNEY AND SHETLAND
BRITISH REGIONAL GEOLOGY
INDEX MAP SHOWING THE REGIONS INTO WHICH THE COUNTRY IS DIVIDED FOR DESCRIPTION IN HANDBOOKS OF THIS SERIES
N
NORTHERN HIGHLANDS
GRAMPIAN HIGHLANDS
TERTIARY VOLCANIC DISTRICTS (AREA SHOWN STIPPLED)
MIDLAND VALLEY
SOUTH OF SCOTLAND
NORTHERN IRELAND
NORTHERN ENGLAND
THE PENNINES AND ADJACENT AREAS
EAST YORKSHIRE AND LINCOLNSHIRE
NORTH WALES
CENTRAL ENGLAND
EAST ANGLIA
THE WELSH BORDERLAND
SOUTH WALES
BRISTOL AND GLOUCESTER
LONDON AND THAMES VALLEY
THE WEALDEN DISTRICT
HAMPSHIRE BASIN
SOUTH-WEST ENGLAND

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London.

Front Cover

The Eildon Hills near Melrose, from Scott's View. The hills are the denuded remains of a composite laccolith of trachytic rocks intruded into the Upper Old Red Sandstone in Carboniferous times.

Plate I—*Frontispiece* (*overleaf*)

Siccar Point, Berwickshire. The south-eastern side of the headland is formed of Silurian greywackes and shales capped by red sandstones and breccias of the Upper Old Red Sandstone. The older rocks are strongly folded on east-north-eastward axes, the beds on the headland dipping very steeply towards the camera. The red sandstones rest on a highly irregular surface of the greywackes which has a general northward slope parallel to the relatively gentle dip of the sandstones themselves. The gully left of centre follows a fault which throws the sandstones down towards the south-east. (Geol. Surv. Photo. No D.1228).

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British Regional Geology

The South of Scotland

(THIRD EDITION)

By D. C. Greig, MA, B Sc

with chapters by

G. A. Goodlet, MA, G. I. Lumsden, BSc, FRSE and
W. Tulloch, BSc

EDINBURGH
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FOREWORD TO THE THIRD EDITION

Few alterations had been made to 'The South of Scotland' since the first edition by the late Dr J. Pringle was published in 1935. The chapters concerned with the Lower Palaeozoic systems have now been completely revised to take account of the revolution of ideas concerning the stratigraphy and structure of these systems and also the large volume of other research which has been undertaken in recent years. Furthermore important contributions to the understanding of the Carboniferous and post-Tertiary geology of the region had rendered obsolete most of the original descriptions of these systems. Recent developments in structural geology, sedimentology, and geochronology which have a relevance to the rocks of the South of Scotland have been incorporated in the appropriate sections of this edition, and the opportunity has also been taken to bring up-to-date the bibliography of the regional geology. The lists given are by no means exhaustive, but are designed as an introduction and to guide the reader to further relevant literature.

Mr Greig has revised the chapters dealing with the Lower Palaeozoic, New Red Sandstone, Tertiary and the economic geology and has also compiled the whole account. The chapter on the Old Red Sandstone has been prepared by Mr W. Tulloch, those on the Carboniferous and on the Volcanic Rocks of Carboniferous Age by Mr G. I. Lumsden, and the late Mr G. A. Goodlet contributed the account of the Pleistocene and Post-Glacial periods.

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20th May, 1971

K. C. DUNHAM
Director

An EXHIBIT illustrating the Geology and Scenery of the district described in this volume is set out in the Geological Museum, Exhibition Road, South Kensington, London SW7

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1. INTRODUCTION

Summary of Geology

The South of Scotland is the region lying between the English border and the Southern Upland Fault, which crosses the country from Loch Ryan to Dunbar. For convenience of description an area of Lower Palaeozoic rocks north of the Fault near Girvan is also included in this account. (Plate XIII).

The geological formations present are:

RECENT and PLEISTOCENE		Soils, blown sand, peat, river and lake alluvia. Raised beach deposits. Solifluxion deposits. Fluvio-glacial sand and gravel. Glacial moraines and boulder clay.
TERTIARY		Tholeiite dykes.
NEW RED SANDSTONE		Trias. Annan Series: red sandstones, shales, and marls. 'Permian'. Red desert-sandstones and breccias. Lavas and agglomerates.
Unconformity		
CARBONIFEROUS	Coal Measures	Sandstones, shales, mudstones, coal seams, and seat-earths. Some thin marine mudstones in Canonbie area. Late quartz-dolerite dykes.
	Non-sequence or unconformity	
	Millstone Grit Series	Upper beds mainly sandstones with many seat-earths and thin coals, bauxitic clays at Thornhill. Some thin marine shales and limestones. Lower beds of Yoredale facies, sandstones, mudstones, limestones, coal seams and seat-earths. Thin basaltic lava at Loch Ryan.
	Carboniferous Limestone Series	Upper beds of Yoredale facies, sandstones, mudstones, limestones, coal seams, and seat-earths. Lower beds mainly sandstones, with mudstones and thin cementstones. Basaltic lavas and tuffs, volcanic vents and acid and basic intrusions, especially near base.
OLD RED SANDSTONE	Upper Old Red Sandstone	Conglomerates, sandstones, marls, cornstones.
	Unconformity	
	Lower Old Red Sandstone	Conglomerates, sandstones, cornstones, lavas, agglomerates, acid intrusions.

Unconformity		
SILURIAN	Wenlock	Riccarton and Raeberry Castle beds; greywackes, shales and fossiliferous grits. Upper part of Dailly Series near Girvan; shales and fossiliferous grits.
	Llandovery	Birkhill Shales in Moffat area. Gala Group; greywackes, flags, and shales, with bands of conglomerate and grit. Dailly Series (lower part) and Newlands Series in Girvan area; greywackes, flags, shales, limestones, and conglomerates.
ORDOVICIAN	Ashgill	Upper Hartfell Shales in Moffat area. Shales and greywackes with limestones and conglomerates elsewhere, e.g. upper part of Portpatrick Group. Upper part of Ardmillan Series of Girvan; sandstones and shales, with limestones and conglomerate.
	Caradoc	Lower Hartfell Shales and Glenkiln Shales in Moffat area. Shales, greywackes, and conglomerates elsewhere, e.g. lower part of Portpatrick Group and Kirkcolm and Corsewall groups. Lower part of Ardmillan Series and Barr Series of Girvan; conglomerates, sandstones, shales, limestones, and greywackes. Lavas, tuffs, and intrusions.
	?Llandeilo	Lavas, cherts, and mudstones.
	Unconformity	
	Arenig	Lavas, pyroclastic rocks, cherts, and mudstones; basic and acid intrusions.

The geological map (Plate XIII) shows clearly that by far the greater part of the region is occupied by Ordovician and Silurian sediments, which form the broad zone of dissected high land known as the Southern Uplands. The oldest, Arenig, rocks occur principally between the Southern Upland Fault and Girvan, and elsewhere form only small isolated outcrops. The map also shows that these Lower Palaeozoic rocks lie in zones which become progressively younger towards the south-east, but, as will be seen in Chapter 2, the disposition of the strata is much more complicated than this broad pattern suggests. In general terms the Old Red Sandstone and younger rocks form a low-lying fringe on the south-east side of the Uplands, but in places they occur in valleys and broad depressions within the Uplands themselves. The Lower Old Red Sandstone lavas along the border south of Kelso occupy high ground which is part of the Cheviot Hills. In the north-east the small area of Lower Carboniferous rocks south-east of Dunbar constitutes an extension of the adjacent large area of similar rocks to the west of that town.

The absence of sediments younger than those of the New Red Sandstone does not imply that no such rocks were ever deposited in the area, but any which were have been removed by subsequent erosion.

Physical Features

The geological diversity introduced into the Lower Palaeozoic by the granitic intrusions of the south-west is reflected by a more rugged topography

in Wigtownshire and Kirkcudbrightshire, where rock-ridges, corries, and hill-lochs participate in a landscape of almost Highland aspect. Here are the highest hills of the region, the Merrick, 842 m, and the Rhinns of Kells, 813 m, composed of metamorphosed sediments close to the Loch Doon Granite. Cairnsmore of Carsphairn, east of Loch Doon, and Cairnsmore of Fleet, to the south, are granite hills over 700 m in height. The highest hills of unaltered Lower Palaeozoic rock lie near the headwaters of Tweed and Annan, where Broad Law, White Coomb, Hart Fell, and other summits all exceed 800 m. The summit-levels decline towards the north-east, the highest hills of the Moorfoot and Lammermuir hills, south and south-east of Edinburgh, being Blackhope Scar, 651 m, and Meikle Says Law, 533 m. North-east of Nithsdale the characteristic smoothly rounded form of the Upland landscape results from the general uniformity of rock-type in the Lower Palaeozoic sediments. In the low ground adjacent to the Solway and in the lower reaches of the Tweed the scenery is locally diversified by geological variations. The granite of Criffell (Plate VIB), the intrusive trachytes of the Eildon Hills (Front cover and Plate XIB), and various intrusive rocks of the Jedburgh area all form isolated hills of varying extent.

The principal drainage of the region is southwards towards the Solway and eastwards, by the Tweed, to the North Sea. In the south-west the rivers Stinchar, Girvan, and Doon flow northwards and westwards into the Firth of Clyde. The Clyde itself rises well within the region, whereas the headwaters of the Tweed system lie in part in the Midland Valley. In general the main watershed between the Midland Valley drainage and that of the Solway–Tweed lies close to the north-western limit of the Southern Uplands, and the highest ground of the Uplands is in the same area. Recognition of these facts has led to the view that the main south-eastward-flowing rivers are but the beheaded remnants of greater ancestors which had their sources far to the north-west. Moreover it has long been realized that the main directions of drainage are unrelated to the outcrop pattern of the rocks, that the streams appear to have been superimposed from an overlying surface of a different geological nature, now completely eroded away, and that in places, for example near Biggar, the main watershed lies in a wide flat valley which clearly at one time carried through-drainage. The drainage pattern is believed by George to have been initiated in late Tertiary times on a benched surface formed possibly during a prolonged period of intermittently falling sea-level. A view expressed earlier by Linton is that the initial surface was an eastward slope of Cretaceous rocks extending from the Grampians to northern England and dating from the later stages of the Cretaceous period.

There is considerable evidence of river-capture in the upper reaches of the Nith, Annan, Clyde, and Tweed. The upper part of the Nith follows an anomalous course, leaving and then re-entering the Southern Uplands in a broad U-turn past New Cumnock towards the Carboniferous outlier of Sanquhar. George describes the Nith as a composite stream, the upper section of which originally flowed northwards towards Cumnock, and the Sanquhar section north-westwards as part of the Upper Clyde, which itself at that time probably joined the Tweed by way of the Biggar Gap. The antiquity of the present course of the upper Nith is shown by the recognition of the buried channel of its pre-Glacial or inter-Glacial ancestor flowing south-eastwards through the New Cumnock Gap.

The Lyne flows south-eastwards from its source in the Pentlands across the lower land beyond West Linton, before entering the Ordovician uplands to join the Tweed above Peebles. Prior to their capture by the Clyde the streams near Carstairs may have followed a similar course towards the Tweed. The rivers of the Tweed basin may be guided by Caledonian tectonic trends, either on east-north-easterly lines or at right angles to them, and in parts of its lower reaches the system appears to follow the axial region of a broad downwarp which also probably originated in Caledonian times.

History of Research

Interest in the geology of the South of Scotland goes back to the very beginnings of the science, notably to the examination by James Hutton in the late 18th century of the unconformities near Jedburgh, and at Siccar Point (Plate I) on the Berwickshire coast. His interpretation of the phenomena displayed at these localities was embodied in his *Theory of the Earth*, published in 1795, and incorporates principles fundamental to scientific geology. The earliest laboratory experiments in the production of folds were carried out by his friend and collaborator, Sir James Hall, inspired by the impressive folding of the Silurian rocks of the Berwickshire coast (Plate IIB). Sir James also recorded his views that the granite of Loch Doon had been emplaced from below, as a liquid, into the Silurian rocks, and that some of the convolutions of these rocks were due to the dynamic effects of this process. Early discoveries of graptolites in the Lower Palaeozoic shales were described by Carrick Moore and Nicol in 1840 and 1841, and both these authors made significant subsequent contributions to the geology of the Lower Palaeozoic rocks, which included stratigraphical correlation with Wales and structural interpretation. Further advances in this field were made by Harkness and Salter, and in 1850 their work was complemented by investigations by Murchison and Sedgwick, with their knowledge of the Lower Palaeozoic systems of Wales and the Welsh Border.

The early work of the Geological Survey in Scotland led to the publication in the 1860's of accounts of areas of Ayrshire, East Lothian, and Berwickshire, prepared by Sir Archibald Geikie and his staff. During this period the Survey was also engaged in the Leadhills area and between Moffat and the south-west coast.

These researches had raised numerous problems of succession, correlation, and structure within the Lower Palaeozoic rocks to many of which the extended and detailed work of Charles Lapworth was to offer a solution. Between his account in 1870 of the Galashiels area and that of Ballantrae published in 1889 Lapworth built up a structural hypothesis concerning the Southern Uplands based largely on field observation and the study of graptolite faunas, which was explained in detail in the second part of the latter paper. His hypothesis was generally accepted until the recent phase of research began in the 1950's. Lapworth's investigations were succeeded from 1888 by a re-examination of the Southern Uplands by Peach and Horne of the Geological Survey. This work culminated in the publication in 1899 of a comprehensive memoir on the Silurian rocks of Scotland, from which the progress of research so far described has been condensed. As a work of reference to geological localities and to earlier literature this publication is of unparalleled value.

Lower Palaeozoic research in the first half of the present century was confined largely to the Girvan and Ballantrae areas. Brachiopods and trilobites were described by Reed in a number of papers and Balsillie studied the Ballantrae Igneous Complex. Other important contributions were made by Dewey and Flett, Begg, Lamont and Bulman. The Ballantrae rocks were most recently described in two papers by Bailey and McCallien. The Geological Survey memoir of 1949 on Central Ayrshire includes a discussion of the general classification of the Ordovician and an account of the stratigraphy of the Craighead Inlier.

Since 1950 there have been several local investigations using modern techniques in sedimentology, petrology, palaeontology, and structural geology, from which has evolved a view of Lower Palaeozoic structure and stratigraphy different in essence from that of Lapworth. Details of this continuing work are given in Chapter 2.

Prior to the 1920's studies of the Old Red Sandstone in the region were in the main of a general type, either forming but part of the descriptions of large areas, as in Geikie's publications on ancient volcanoes and on the Old Red Sandstone of Western Europe, or dealing in a general way with the rocks of the system in a part of the region. Between 1887 and 1890, however, appeared three detailed accounts of metamorphic and igneous phenomena in Kirkcudbrightshire and Berwickshire. A comprehensive account of the Galloway granites, with some details of other intrusive masses, is given by Teall in the Geological Survey memoir of 1899 on the Silurian rocks of Scotland. Arid conditions during the deposition of the Upper Old Red Sandstone were suggested by Goodchild in a paper of 1903. In the same year a lithological account of the Upper Old Red Sandstone near Canonbie was given by Peach and Horne, and the same rocks as they occur in East Lothian were described in the 1910 memoir on that area by Clough and his collaborators.

In subsequent years research work has been directed much more towards the igneous rocks of the Lower Old Red Sandstone than to any other parts of the system. In the late 1920's a number of papers dealt with the smaller intrusions, and in the 1930's the large granite masses of the south-west were described in a series of papers by Gardiner and Reynolds, Deer, and Malcolm MacGregor. Studies of smaller intrusions were published during the succeeding decade. In the years prior to 1939 members of the Geological Survey were engaged in the eastern Borders, and published several reports on the Upper Old Red Sandstone sediments and associated igneous rocks. Since 1950 a number of specialized investigations have been carried out in such fields as geochemistry, geophysics, radiometric dating, metamorphism and sedimentology. The large intrusions of the south-west have continued to attract the major part of the research, but important new palaeontological finds have been reported from Duns, and the Geological Survey has published a comprehensive account of the Upper Old Red Sandstone in the Langholm area.

Much of the early work on the Carboniferous system was done by officers of the Geological Survey. The Canonbie Coalfield was described in 1903 by Peach and Horne in the paper already mentioned, and in 1910 the coastal area south-east of Dunbar was described in the East Lothian memoir by Clough and his colleagues. The first detailed account of the outliers at Sanquhar and Thornhill was given by Simpson and Richey in 1936, and the

report of a wartime resurvey of the Canonbie Coalfield by Barrett and Richey was published in 1945.

Since the war there has been detailed study by Craig and Nairn of the outcrops on the Solway coast, and resurveys of the Langholm area and of the Sanquhar outlier by the Geological Survey. Knowledge of the Carboniferous geology of the Canonbie area was greatly increased by the Geological Survey's deep borehole at Archerbeck, described in 1961 by Lumsden and Wilson. Little has been published on the Carboniferous rocks of Berwickshire apart from a recent description of the sandstone sedimentation. The relevant results of the Geological Survey's recent resurvey of East Lothian are incorporated in this account. A valuable description of the region as a whole was given by George in his 1958 account of the Lower Carboniferous palaeogeography of the British Isles

A general description of the volcanic rocks of Carboniferous age was given in 1897 by Geikie in his account of the ancient volcanoes of Britain. In two papers published in 1914 and 1920 Lady McRobert described the igneous rocks around Melrose and in the country south-westwards to Langholm and Canonbie. An account of the Kelso Traps by Eckford and Ritchie was published in 1939, and detailed accounts of the Birrenswark Lavas by Pallister and by Elliott appeared in 1952 and 1960. Additional descriptions of igneous rocks in Roxburghshire were given by Tomkeieff in the 1950's. The igneous rocks of the Langholm district are fully described in the Geological Survey memoir on that area, published in 1967.

The distinctive nature of the New Red Sandstone sediments was noted by Binney in 1856, but the principal stratigraphical accounts are those of Simpson and Richey in 1936 on the Sanquhar and Thornhill basins, and of Horne and Gregory in 1916 and Barrett in 1942 on the Annan basin. Studies of igneous intrusions by Scott and by Walker were published in 1915 and 1925. In recent years there have been gravity surveys of the Dumfries and Stranraer areas, published in 1960 and 1963.

Research into the problems of the Tertiary igneous rocks has in most cases dealt with the South of Scotland only as part of the Tertiary Volcanic province of Scotland and Northern Ireland. In 1880 Geikie published petrographic details of the Eskdalemuir dyke and presented a general hypothesis concerning the genesis of the Tertiary igneous rocks. Elliott's account of the same dyke, published in 1956, is in some ways complementary to Geikie's, with additional and more specialized petrological discussion. The Geological Survey memoir on Central Ayrshire, published in 1949, includes details of intrusions in a small area between the Southern Upland Fault and the Cairnsmore of Carsphairn Granite.

The first account on modern lines of the glaciation of the South of Scotland was given in 1926 by Charlesworth, and in 1956 George described the development of the drainage pattern of the central part of the Southern Uplands. Otherwise research in the last few decades has been more specialized in terms of the geographical area studied or of the scope of the subject. The main fields of study have been phenomena of glacial retreat by Sissons and Price, palaeobotany and radio-carbon age determination by Erdtman, Mitchell, and Jardine, and post-glacial changes in sea-level by Sissons and Donner. Sand and gravel deposits have been studied from both a philosophical and an economic point of view by Bailey and Eckford and by Goodlet. In its recent and current

work in Ayrshire, the Langholm area, East Lothian, and Berwickshire the Geological Survey has paid considerable attention to the distribution of Glacial and Post-Glacial deposits and to their historical interpretation.

Research in the field of economic geology has been carried out principally by officers of the Geological Survey and by individuals engaged by them for the purpose. It is published in two main phases, the Special Reports on the Mineral Resources, which were initiated during the period of the Great War, and the Wartime Pamphlets which arose from the exigencies of the Second World War. In more recent years the Geological Survey has published a complete record of sources of underground water in the region, and reports on sources of road aggregate and on sand and gravel. In addition to the work of the Geological Survey the Leadhills–Wanlockhead district was studied in the 1950's by Temple and by Mackay and his colleagues, and research into the resources and uses of peat was promoted by the Department of Agriculture and Fisheries for Scotland.

2. LOWER PALAEOZOIC ROCKS

Lower Palaeozoic rocks of the Ordovician and Silurian systems form the Southern Uplands, the principal physical feature of the South of Scotland. In contrast to the younger formations the beds are strongly folded, the predominant trend of the structures being between north-east and east-north-east. These rocks are mainly greywackes, a form of sandstone with a variety of mineral and rock fragments and a paste-like matrix of the same material, and finer-grained siltstones and shales. They were deposited on the floor of an elongate marine trough, which was at the time evolving in response to the deep-seated stresses of the Caledonian earth-movements and to the weight of the sediments themselves. The early Ordovician rocks exposed in places between north-west Scotland and North Wales give no clear indication of the form of the area of deposition at that time, but in late Ordovician time and in the Silurian, when the rocks of the Southern Uplands were being laid down, the trough, or geosyncline, appears to have extended from south-west to north-east between fluctuating shore-lines which lay in the Scottish Highlands and the English Midlands. The greywackes and shales are of deep-water origin. The shales are most persistently developed along a north-eastward 'axis' passing through Moffat, which has been interpreted as the central deep of the geosyncline, remote from sources of sediment, but may represent the line of a submarine ridge too high to receive the greywacke material.

In recent years it has become recognized that the distribution and deposition of the greywackes was effected by submarine turbidity currents which carried large quantities of rock material, and were able to persist, and to preserve their individual identity, over considerable distances. They are believed to have originated on the steep margin of the continental shelf, perhaps under the influence of earthquakes, climatic variations, or as a consequence of gradually increasing instability. As a current gradually lost momentum it began to deposit sediment and quickly built up a bed of sand which, in the general case, became progressively finer in grain from the base to the top. The currents and the material carried by them in many cases eroded the soft material on the sea-floor so that the sand was in time deposited on a channelled or grooved surface. As a result the under-surface of many a bed of greywacke is now seen to be intricately patterned by the projecting casts of such channels (Plate V), most commonly flute-casts and groove-casts, the latter caused by the dragging of rock-fragments along the sub-stratum. The direction of current is parallel to the elongation of the casts, and the bulbous ends of the flute-casts mark the upstream direction. The most common direction of flow in the Southern Uplands is either north-eastward or south-westward, parallel to the elongation of the basin. Load-casts are random-oriented bulbous features developed at the base of a greywacke by the downward and sideways squeezing of the underlying mud under the weight of the material above. Transverse current ripple-marks often occur on the

upper surface of a greywacke, in the comparatively fine-grained material (Plate IVB). Organic tracks may occur on the upper surfaces of greywacke units. All these structures, which have been described in detail by Kuenen, Walton and others, are of prime value in determining the tops and bottoms of the beds, which are seldom self-evident.

The stratigraphy of the Lower Palaeozoic rocks of the region was first described by Lapworth in the 1870's and '80's, and his principles were adopted, and extended over the whole region, by Peach and Horne in the comprehensive Geological Survey memoir of 1899. Lapworth's stratigraphical interpretation was based primarily on the succession of graptolites which he found in shales at certain localities, but, recognizing that the main mass of the rock was unfossiliferous, he formed the opinion that the recurrence of shales with similar faunas must represent repetition of the same bands of rock, brought about by folding. In the Southern Uplands these shales were thought to crop out in elongate boat-shaped anticlinal inliers. Tight folding is often conspicuous in the fossiliferous shales to which Lapworth devoted much of his attention, and the rocks in general were thus considered to be affected by such folds, so that relatively thin series of steeply dipping, oft-repeated beds were regarded as forming the broad formational outcrops of the Southern Uplands. Open folding superimposed on these tight structures was thought to be responsible for the present disposition of the major formations, the Ordovician rocks in the north-west being exposed in the axial region of an anticlinorium, the Leadhills Endocline, and the Silurian rocks being preserved to the south-east in the complementary synclinorium, the Hawick Exocline (Fig. 1). The three parallel outcrops of Ordovician, Llandovery, and Wenlock rocks were described respectively as the Northern, Central, and Southern belts.

Research carried out in different parts of the region during the last 20 years has prompted the widely held opinion that Lapworth's general interpretation of the structure, and in consequence his views on formational thicknesses and some of his stratigraphical conclusions, are incorrect. The new interpretation owes much to the advances in sedimentology and the study of sedimentation structures referred to above, in correctly determining the order of succession of strata. The broad structural pattern now envisaged for the whole of the Southern Uplands is one of alternate zones of steeply dipping beds, becoming younger to the north-west, and of closely folded beds, involving no great thickness of rock, in which the *faltenspiegel*[1] is horizontal or dips at a low angle to the south-east. The effect (Fig. 1) is thus of a series of monoclines or grossly asymmetrical anticlines, facing towards the north-west, which, if uninterrupted, would lead to successively younger rocks coming to outcrop in that direction. The fact that, in broad terms, the opposite is the case is explained by the occurrence, often at the boundaries between the structural zones just described, of large faults with downthrow to the south-east, which outweigh the effect of the folding. Several of these faults are visible and have been described in detail.

With much of the area still to be re-examined in the light of the new techniques it is not yet possible to present a comprehensive revised description of the Lower Palaeozoic and indeed it is clear that there remain major

[1] *faltenspiegel*—In tightly folded beds, a surface tangential to any one stratum across the crests or troughs of individual folds. A 'generalized' bedding-plane.

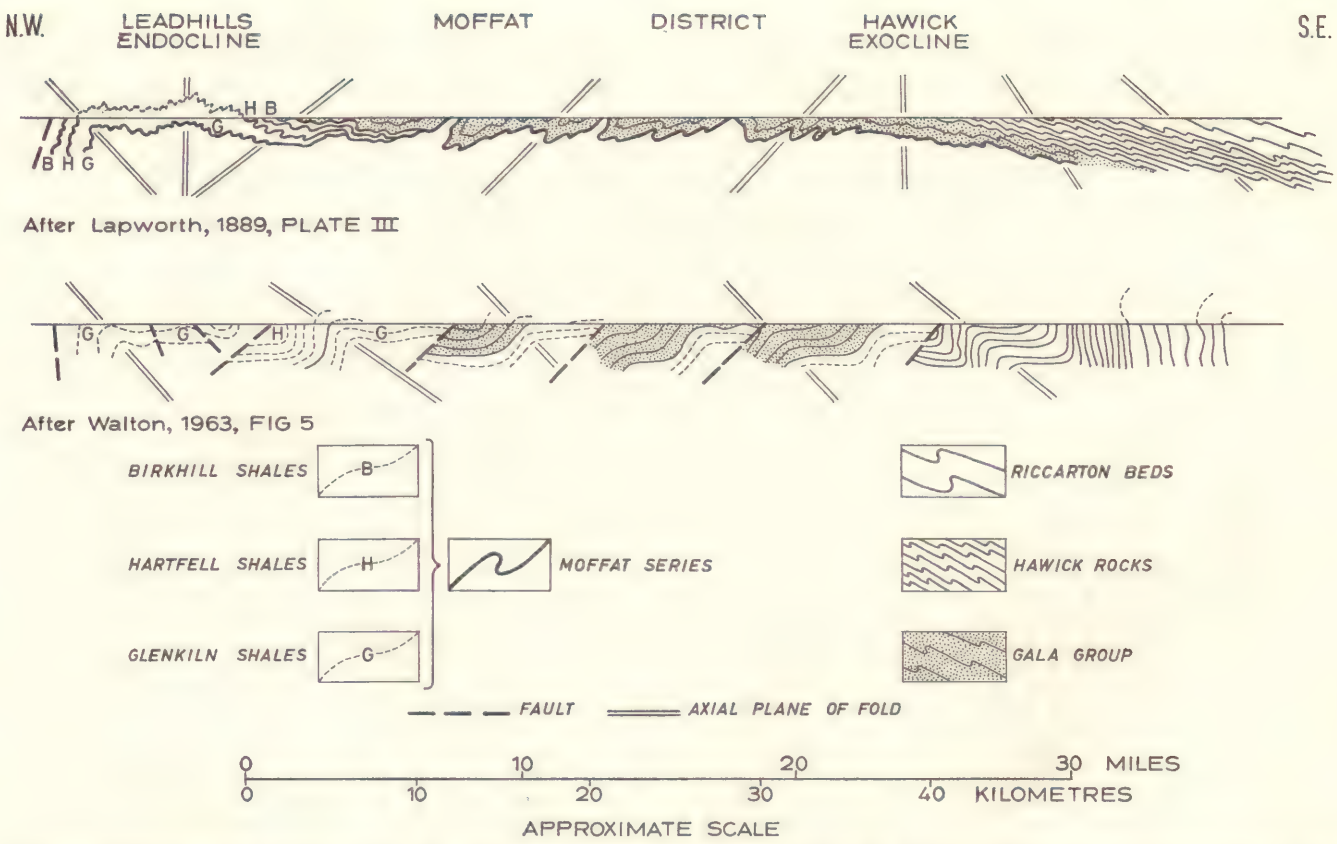


Fig. 1. *Schematic cross-sections from the Southern Upland Fault to the Solway Firth showing alternative interpretations of the structure of the Lower Palaeozoic rocks*

problems of correlation upon which considerable differences of opinion exist. The stratigraphical position of the unfossiliferous Hawick Rocks (p. 35) is an important example of current controversy. Much of the difficulty in the solution of these problems arises from the generally sparse exposure of rock in the Uplands. It is often very difficult, too, to assess the importance, or even to recognize the occurrence, of strike-faults, which collectively play a major part in the structural pattern.

The broad structural pattern in the Southern Uplands is clearly due to horizontal compression in a north-north-westerly to south-south-easterly direction, resulting in folding along east-north-easterly axes and the development of strike-faults. This compression is a late expression of the Caledonian orogeny, which was responsible in several Lower Palaeozoic phases for much of the deformation of the rocks of the Highlands and for the development of the geosyncline in which the sediments of the Southern Uplands were deposited. In recent years detailed structural studies in a number of areas have shown that several tectonic phases are represented.

In each case the main folding, and usually the earliest that can be readily studied, has arisen from a near-horizontal compression in a direction between south-east and south. In some areas this force has tightened up or contorted pre-existing folds formed under broadly similar stress systems and possibly not significantly different in age. Later Caledonian phases are recognized locally, as in Wigtownshire where folds resulting from a north–south compression lie in zones parallel to the prevailing east-north-easterly strike. Near Girvan early folding and thrusting is thought to have led to resistance to continuing vertical relief of pressure and to the development of wrench-faults and horizontal fold-faults. The latest Caledonian movements are responsible for the unconformity between the Lower and Upper Old Red Sandstone.

Reversed strike-faults and subsequent wrench-faults are widely developed in association with the main folding and there is widespread evidence of the later re-activation of many faults under different stress conditions. The Southern Upland Fault, which however may not have originated until the Lower–Upper Old Red Sandstone interval, presents a notable example of re-activation. In the Galloway peninsula it is mapped as a normal fault but there are also indications of later strike-slip movement. In upper Nithsdale there is evidence of normal displacement in the Pleistocene. There is some controversy as to the tectonic processes responsible for the many oblique-slip faults and for many of the complexities of folding, and in consequence as to the detailed tectonic history of the region.

Although they lie within the Midland Valley the Lower Palaeozoic rocks of the Ballantrae and Girvan area (Figs. 2 and 3) are described here since they were originally studied by Lapworth in relation to those of the Southern Uplands, to which they are physically adjacent. Whereas the late Ordovician and Silurian rocks of the Southern Uplands are rarely of shallow-water origin those of Girvan are predominantly so, having apparently been deposited in an archipelago of islands of Arenig rock. Extensive outcrops of the Arenig are restricted to this area. For clarity the contrasting rocks of the two areas are described separately.

3. ORDOVICIAN

The Ordovician System in Britain is divided into a number of series which take their names from localities in Wales, Shropshire, and the Lake District. Graptolite studies begun by Lapworth at Moffat in the 1870's have led to the further subdivision of the system into thirteen zones, each with a characteristic assemblage of graptolites, and on this basis the rocks of the South of Scotland can be fitted into the classification, as shown in the table opposite. Peach and Horne recognized the stratigraphical break between the Arenig and Caradoc rocks only in the Girvan area, but it is now widely, though not universally, accepted that the break exists throughout the Southern Uplands. It has been suggested however that it is more apparent than real, the Llanvirn and Llandeilo rocks being unfossiliferous, and Llandeilo rocks have recently been reported to occur at several localities.

An outstanding feature of the Caradoc Series, first pointed out by Lapworth, is the change which takes place in the rocks as they are followed from Girvan to Moffat. At Girvan there are at least 2400 m of neritic rocks, conglomerates, sandstones, shales, and shelly limestones, which are abruptly replaced beyond the River Stinchar, some 8 km to south-east, by an equally thick series of greywackes, with conglomerates, spilitic lavas, and cherts. Greywackes with black graptolitic shales pass, across the width of the Northern Belt, into a thinner and predominantly shaly succession which reaches its ultimate expression in the Moffat area, where the whole series is represented by 18 m of shales and cherts. The same type of change is seen in the Ashgill Series and in the lower part of the succeeding Llandovery Series, but in these formations equivalent stages in the transition from a greywacke to a shale succession occur progressively farther to the south. Less conclusive evidence is seen of a complementary reversal of this change as the beds are followed south-eastwards from Moffat.

Arenig Rocks: Ballantrae Igneous Complex

The Ballantrae Igneous Complex comprises a group of spilitic lavas and pyroclastic rocks, with associated cherts and fossiliferous shales, and a number of major and minor intrusions. These rocks crop out on the Ayrshire coast between Ballantrae and Kennedy's Pass and extend inland for some 5 to 10 km to the north-east (Fig. 3). The Middle Arenig age of some of the lavas is proved by the occurrence in associated black shales of several species of the genus *Tetragraptus* and of *Didymograptus extensus*, all characteristic of the Zone of *D. extensus*.

The lavas and pyroclastics are intensely folded and are typically exposed at Bennane Head where the succession is:

Series	Zones	Moffat Area	Girvan Area	Northern Belt	Geological Survey (Peach and Horne) 1899
Ashgill	*Dicellograptus anceps* *Dicellograptus complanatus*	Upper Hartfell Shales	Ardmillan Series	Lowther Shales with conglomerates and greywackes Black shales passing laterally into greywackes, shales, and conglomerates. Some limestones. Volcanic rocks in middle zone	Caradoc
Caradoc	*Pleurograptus linearis* *Dicranograptus clingani* *Climacograptus wilsoni*	Lower Hartfell Shales			
	Climacograptus peltifer *Nemagraptus gracilis*	Glenkiln Shales	Barr Series	Black shales passing north and west into grits, greywackes, and shales. Volcanic rocks at Bail Hill, etc.	Upper Llandeilo
Llandeilo	*Glyptograptus teretiusculus*	?		?	
Llanvirn	*Didymograptus murchisoni* *Didymograptus bifidus*		Unconformity		
Arenig	*Didymograptus hirundo* *Didymograptus extensus*		Ballantrae Igneous Complex ?		Lower Llandeilo and Middle Arenig

Classification of the Ordovician System in the South of Scotland

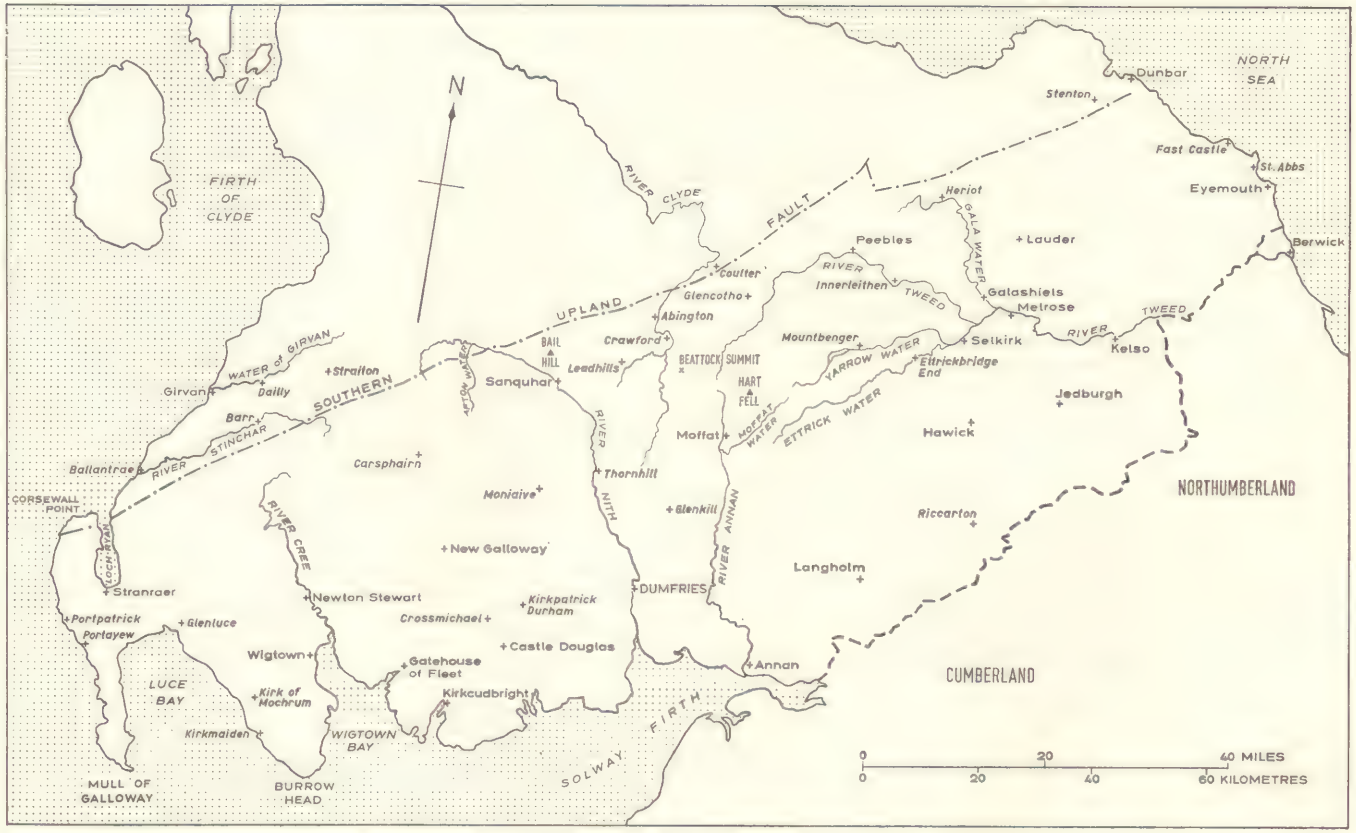


FIG. 2. *Map showing localities referred to in Chapters* 3 *and* 4

	metres
Red, green, and grey radiolarian cherts interstratified with tuffs and volcanic breccias	20
Bedded coarse-grained agglomerates and tuffs, with a thin bed of fossiliferous black shale within 6 m of the top . . about	200
Spilitic lavas, occasionally associated with agglomerates and tuffs, and including two thin bands of fossiliferous tuffaceous mudstone at least	200

The base of the lavas is not exposed. In addition to the graptolites the fossiliferous beds contain small horny brachiopods, such as *Acrotreta* and *Lingula*, and a crustacean *Caryocaris wrighti*.

Bailey and McCallien recognized two distinct groups of spilites, the Knockdolian and Downan Point groups, lying respectively below and above the widely occurring serpentinite. The main outcrops of all these rocks are shown in Fig. 3, their southern limit lying near Downan Point, some 7 km south of Bennane Head. The separation of the two groups was not related to any petrographic difference, although earlier work by Teall had described two types of lava, diabase and diabase-porphyrite, the latter distinguished by the presence of large phenocrysts of plagioclase. The rocks have a deeply weathered appearance, the feldspars are altered in varying degree to albite, which is itself replaced by other minerals, and the olivines are in some cases replaced by serpentine. Small vesicles are generally abundant.

A characteristic feature of the spilites is the development of 'pillows' from 0·15 to 0·6 m high and exceptionally 3 m long. They are very well displayed on the shore at Downan Point (Plate IIA), and indicate that the lavas were extruded under water. The pillow-lavas are generally fine-grained, the pillows being typically compact in the centre with layers of vesicles towards, and parallel to, the outer surface. The order of deposition of these highly folded beds may be indicated by a greater abundance of vesicles in the original upper part of a pillow, or by the moulding of pillows against those over which they were formed. The spaces between the pillows are occupied by silica and, near the tops of lava-flows, by limestone.

The agglomerates and tuffs which are associated with the lavas, and may in places comprise the infilling of volcanic necks, are made up of a variety of rock and crystal fragments. Large fragments in a number of areas suggest the proximity of a centre of eruption. An agglomerate at Stockenray Bay, north of Lendalfoot, includes blocks of glassy lava with unaltered feldspar. This has been taken to show that the agglomerate formed prior to the albitization of the lavas, a process from which the blocks in the agglomerate were in some way protected. Alternative views are that the glassy matrix of the lava protected the feldspar, or that the cooling lavas were permeated by volcanic water which prevented the soda-rich sea-water from altering them. Macadam-like agglomerates, composed of angular fragments with very little matrix, occur on Knockdolian and on Prieston Hill near Colmonell. At the latter locality, where the fragments are of albite-granite, the rock has been alternatively described as a concussion-breccia formed in place, or as a volcanic agglomerate derived possibly from a concealed extension of the Byne Hill granite. Certain andesites, basalts, and trachytes are known only as fragments in the agglomerates. Various altered rocks considered to be younger than the serpentinite occur in agglomerates at one locality.

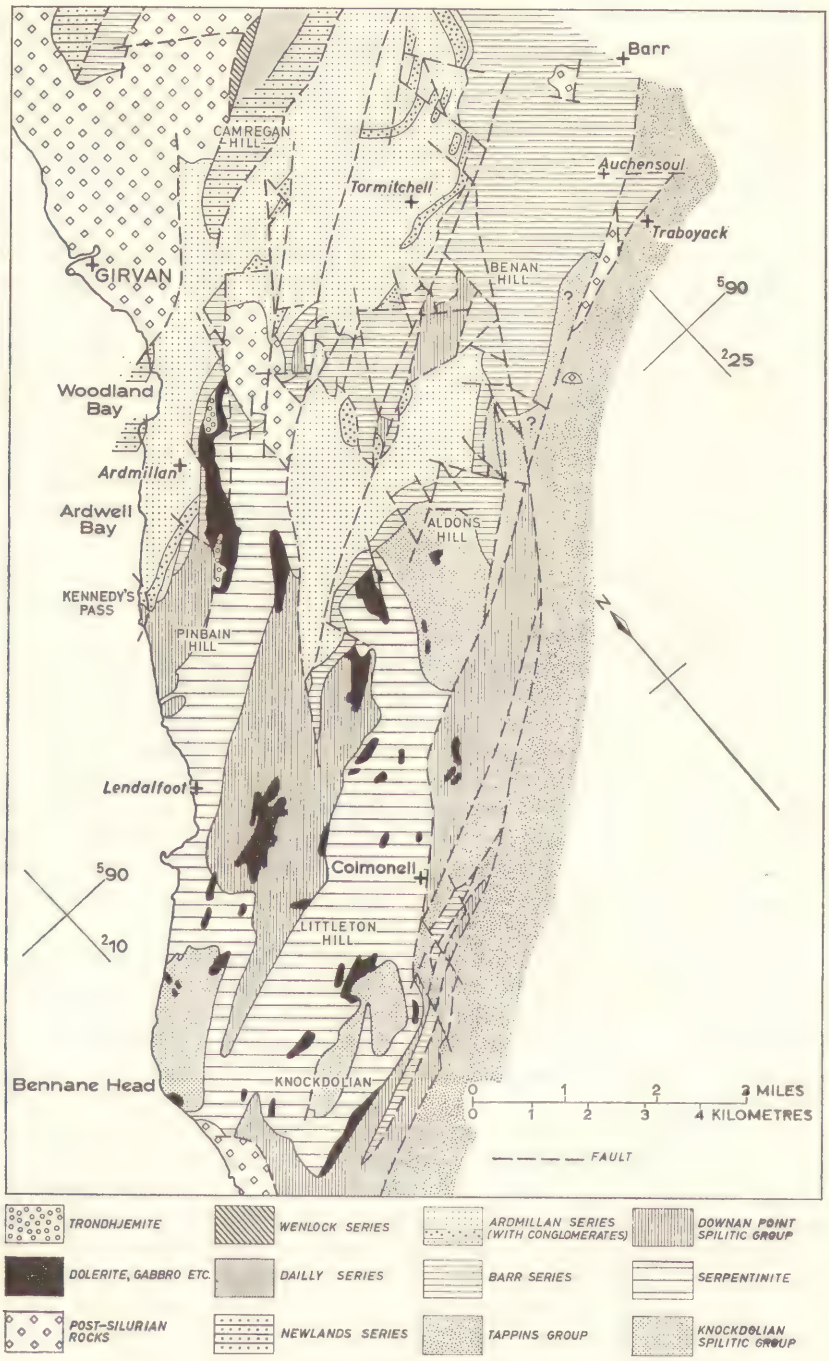


FIG. 3. *Geological map of the Girvan area*

(Based on work of the Institute of Geological Sciences, Bailey and McCallien 1957 and Williams 1962)

The many-coloured shales and mudstones, in some cases tuffaceous, which are intimately associated with the volcanic rocks, have locally yielded valuable faunas of graptolites and inarticulate brachiopods. Chert occurs amongst the lavas and in a series of beds, associated with tuffs and agglomerates, which overlies the graptolitic Middle Arenig shales. Radiolaria can be seen in hand-specimens of the rock but no detailed study of them has yet been made in this area. In places the chert appears to be devoid of radiolaria, and it is probable that the silica was predominantly precipitated by inorganic processes.

Serpentinite crops out in two broad zones extending inland from Bennane Head and Lendalfoot (Fig. 3), bounded to north-west and south-east by Arenig lavas. Several varieties are present, the most common being bastite-serpentinite, of which an example is described as a dark green or black rock with large, lustrous crystals of bronzite. Other varieties are serpentinized dunite, a dark green rock with pale yellow crystals of largely unaltered olivine, and tremolite-serpentinite. Other ultrabasic rocks associated with the serpentinite include picrite, pyroxenite, and bronzitite, the whole assemblage often having a banded appearance. At several localities adjacent to the central spilite zone a schistosity parallel to the boundary is developed in the serpentinite. This has been ascribed to the dynamic effect of intrusion or faulting. In one area the rock is described as a hornblende-schist, derived possibly from both serpentinite and spilite.

Gabbro and dolerite, albitized, granulitized, and foliated in varying degree, occur in many small areas within the serpentinite. They have been interpreted as intrusions into the latter or, in some cases, as xenoliths of older rock caught up and metamorphosed by it. Some authors have regarded them as altered spilitic lavas. Dynamic and thermal metamorphism have been alternatively invoked to explain the wide variety of rocks which is present, and the possible existence of a concealed mass of acid rock below the southern serpentinite has also been postulated. The largest outcrop of these rocks forms the ridge between Grey Hill and Byne Hill, east of Ardwell Bay, and consists of a series grading from gabbro to trondhjemite, a series generally regarded as the product of differentiation of a basic magma.

Many different opinions have been expressed as to the sequence of events in the development of the igneous complex. It is universally agreed that the lavas and associated sediments are of Arenig age and that many of the basic rocks are intrusive into the serpentinite. Peach and Horne held, and most later workers have agreed with them, that the serpentinite was itself intrusive into the spilites, in the form of two thick dykes. The lack of positive evidence for this theory, the lack of contact alteration attributable to the serpentinite, the degree of metamorphism in some of the rocks within the serpentinite, the development of a foliation in the serpentinite which is absent in the spilites, and the occurrence of fragments of the metamorphic rocks in the Arenig agglomerates led Pringle and Balsillie to adopt the view that the serpentinite and the rocks associated with it were pre-Arenig in age, probably Pre-Cambrian. More recently Bailey and McCallien have suggested that the serpentinite may be an ultra-basic submarine lava intermediate in age between a lower and an upper spilite formation. This hypothesis is based primarily on a study of the sequence of rocks at a number of localities, and is supported by the general disposition of the serpentinite outcrops in relation to the

spilites, modified slightly from that shown on the Geological Survey map, and the presence of metamorphic fragments in (upper) agglomerates, as noted by Balsillie. The possibility that the gabbro-granite series of Byne Hill may be part of the pre-Arenig basement has been entertained, even by some workers who have assigned an Arenig age to the other basic rocks within the serpentinite, but differences between the trondhjemite of Byne Hill and the granite fragments in the adjacent Benan Conglomerate led Pringle to suggest that the former might be a post-Benan intrusion.

The albitization of the spilites and of the basic intrusive rocks is considered to be a hydrothermal process active during the consolidation of the rocks. The serpentinite is derived from an original peridotite, modified by hydrothermal solutions at a time shortly after its consolidation, possibly at the time of the emplacement of the basic intrusions. The expansion involved in this process may have been partly responsible for the metamorphism of the crystallizing basic rocks.

Arenig and Llandeilo Rocks: Southern Uplands

Decomposed basic lavas at Raven Gill, near Crawford, are overlain by mudstone containing Arenig graptolites, brachiopods, and conodonts. At some other localities similar lavas were recognized by Peach and Horne to be of Glenkiln or Hartfell age, but in general the occurrence of cherts and mudstones, whether or not associated with volcanic rocks, was taken by these authors to indicate the development by sharp folding of an inlier of Middle Arenig to Llandeilo age. Recent work by Lamont and Lindström has shown that in some instances these sediments yield a conodont fauna of Llandeilian type. The opinion, expressed by Pringle in earlier editions of this publication, that no rocks of Llanvirn or Llandeilo age are present, is thus refuted, although it may still be maintained that there was a hiatus in sedimentation at some time between the Arenig volcanics and the Glenkiln Shales. Spilites associated with the Llandeilian cherts at some localities in Wigtownshire, South Ayrshire, and Peeblesshire, may be said to be of the same age, but at other localities the relationship between the lava and the chert is uncertain and the age of the former cannot be positively stated.

The occurrence together, in many different areas of the world, of pillow-lavas and radiolarian cherts was commented on by Teall in 1894 and it is now accepted that the ultimate source of the silica of the cherts is to be found in the submarine effusion of the lavas. This essential link between the two rocks is emphasized by the frequent occurrence of chert between the pillows of lava, and by the fact that chert may succeed lava but never underlies it. The siliceous environment and conditions favourable to the deposition of the chert can be expected to persist for only a short period after the effusion of the lava, and it may therefore be asserted that lavas and cherts occurring together will be of essentially the same age.

Raven Gill is the only locality at which lavas lying close below Glenkiln Shales have been proved to be of Arenig age. The succession of rocks below the Llandeilian lavas of other localities is quite unknown and their relationship to the Arenig is conjectural.

On Bail Hill, near Sanquhar, cherts which underlie Glenkiln Shales with interbedded lavas are possibly of Llandeilo or even Caradoc age, rather than Arenig as was formerly believed.

Caradoc and Ashgill Rocks: Southern Uplands

The **Glenkiln Shales** in the Central Belt are exposed only in scattered lenticular inliers which were formerly thought to represent the culminations of sharp anticlinal folds. Recent research indicates the importance of strike-faults in determining the occurrence of these inliers, and it is probable that many of them are fault-bounded on their south-eastern margins. The rocks, which are about 6 m thick in the Moffat area, are in general black shales with thin cherty ribs, and grey and orange tuffaceous mudstones with bands of grey radiolarian chert. In the type-section of Glenkill Burn, between Dumfries and Moffat, they consist of black shales yielding, amongst many other species, the following graptolites characteristic of the Caradoc zones of *Nemagraptus gracilis* and *Climacograptus peltifer—Climacograptus bicornis*, *C. peltifer*, *Dicellograptus intortus*, *D. patulosus*, *Didymograptus superstes*, and *N. gracilis*. To the north-east the shales are seen again in several localities, notably at Dobb's Linn, Hartfell Spa, and Ettrickbridge End, between Moffat and Selkirk, but farther to the north-east the general plunge of the fold-axes in that direction carries them below the level of exposure. They occur also in a number of outcrops to the south-west, most notably between Crossmichael and Kirkpatrick Durham, and near the Water of Malzie, some 13 km west-south-west of Wigtown.

More numerous inliers of Glenkiln Shales occur in the Northern Belt. The south-eastern outcrops are like those farther south, but to the north-west the shales are variably interspersed with grey mudstones, sandy shales, and greywackes. This change is accompanied by an increase in overall thickness, to a figure estimated by Peach and Horne to be about 350 m but by Kelling, working in the Galloway peninsula, to be about 1850 m. Kelling also observed that at Portayew, close to the southern margin of the Northern Belt, Glenkiln shales and cherts are only about 9 m thick. At Leadhills shales of Glenkiln and Hartfell age are seen to be bounded to the south-east by reverse-faults which hade north-westwards. The younger Ordovician greywackes beyond the faults are traversed by important veins of galena and zinc blende.

Farther to the north-west, between the Southern Upland Fault and the River Stinchar, rocks of Glenkiln age, and possibly somewhat older, constitute the Glen App and Tappins groups which include graptolitic shales, but consist mainly of greywackes and siltstones, with thick conglomerates in the older Glen App Group. Spilites and cherts are present in the basal subdivision of the Tappins Group, and higher beds have yielded a trilobite fauna closely similar to that of the *Didymograptus superstes* Mudstones of the Barr Series. Williams has estimated the thickness of the Tappins Group to be about 2450 m in contrast to the 150 m of isoclinally folded beds described by Peach and Horne.

In the Rhins of Galloway Kelling divided the Glenkiln rocks into the Corsewall and Kirkcolm groups, approximately correlative with the Glen App and Tappins groups. The Corsewall Group, which crops out north of the Southern Upland Fault, contains chaotic slide-conglomerates derived from the north-west, interspersed with laminated and current-bedded greywackes and siltstones laid down in shallow water. The greywackes and siltstones of the Kirkcolm and Portpatrick (p. 23) groups are predominantly deep-water turbidites. The upward succession shows a progressive variation in source-

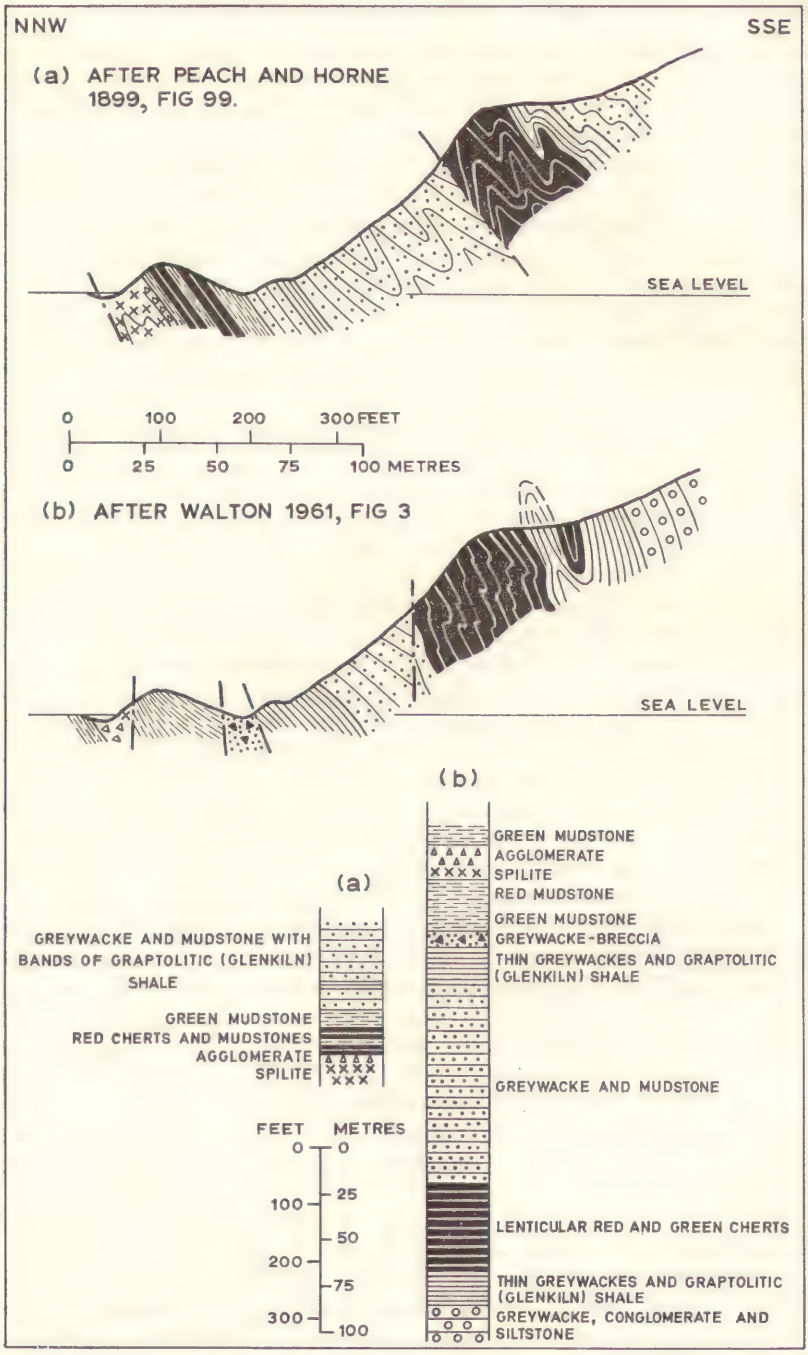
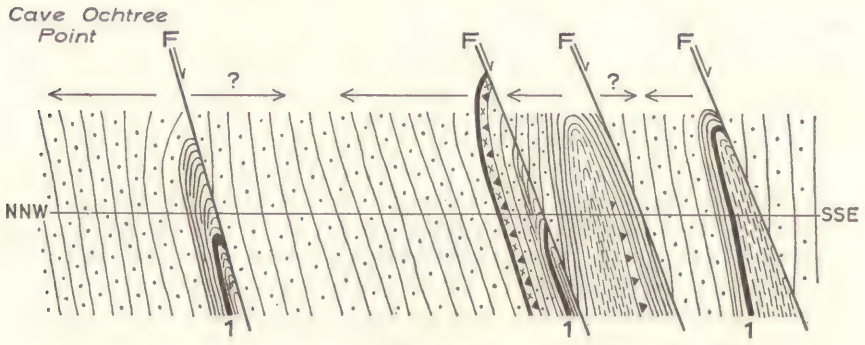


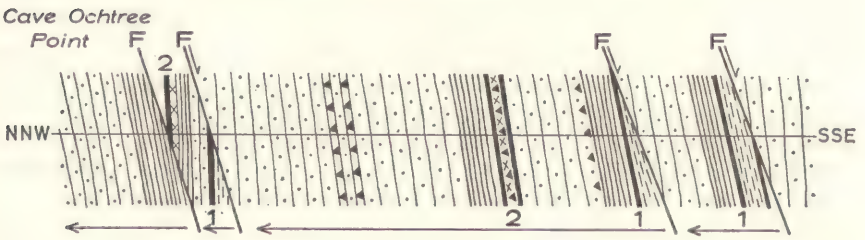
FIG. 4. *Alternative interpretations of structure and stratigraphy in Ordovician rocks at Portandea, south of Ballantrae*

rock, from igneous rocks of local type to metamorphic rocks from farther north.

Kelling and Walton have shown that several lithologically distinctive bands of shale with Glenkiln graptolites can be recognized (for example in the Glen App and Tappins groups and throughout the Kirkcolm Group)



(a) Horizontal cross-section based on the work of Peach and Horne 1899, pp. 413–5, and on their unpublished six-inch map. One band of Glenkiln shale, repeated by folding.



(b) Horizontal cross-section based on the work of Kelling 1961, pp. 45–7. Two bands of Glenkiln shale, repeated by faulting.

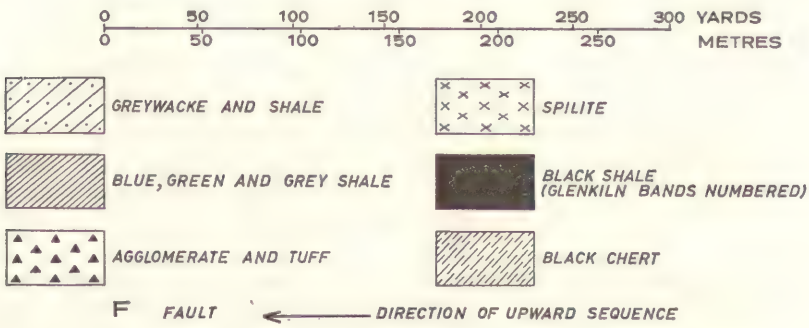


FIG. 5. *Alternative interpretations in Glenkiln Shales and associated rocks near Portslogan in the Rhins of Galloway*

interbedded with greywackes, as are the volcanic rocks with which they are in many cases associated. In general the rocks young towards the north-west and there is no doubt that such repetition as may occur is due mainly to strike-faulting and not to folding, of which there is apparently no important development (Figs. 4 and 5). It is reasonable to suppose that this is the general pattern of sequence and structure throughout the north-western part of the Northern Belt, and that the facies change from graptolitic shale to greywacke was of a more oscillatory nature than Peach and Horne seem to have thought. A corollary of the newer interpretation is that the total thickness of the Glenkiln rocks must be considerably greater than was inferred from the hypothesis of tight-folding and continued repetition of horizons.

The **Hartfell Shales** are typically developed on the 'Score' at Hartfell Spa, 7 km north of Moffat, and form the middle member of the graptolitic shales of that district, the Moffat Series. They are about 30 m thick and typically comprise a lower group of graptolitic black shales with thin partings of pale mudstones, and an upper group, the Barren Mudstones, of mudstones with beds of black shale. They are in general lithology similar to the Glenkiln Shales, which they follow with no apparent stratigraphical break. At Ettrick-bridge End, near Selkirk, the most south-easterly outcrop of the Moffat Series, there is however an important change in the lithology of the Barren Mudstones which here comprise about 55 m of greywackes with thin bands of green shale and fossiliferous black shale. Some of the shales include bands and nodules of limestone similar to the Wrae Limestone of Peeblesshire (p. 24).

The Lower Hartfell is richly fossiliferous, with many species of graptolites and an abundance of the horny brachiopods *Acrotreta* and *Siphonotreta* and of the sponge *Hyalostelia*. The great abundance of certain species of graptolite on individual bedding-planes has been taken to indicate frequent interruption of the deposition of sediment. By contrast the fauna of the Upper Hartfell is rather sparse, graptolites occurring only in thin dark beds interbedded with the barren mudstones. Lapworth drew attention to the fact that most of the graptolite genera of the Hartfell Shales die out before the highest beds are reached. There is thus a marked faunal break between the Ordovician and Silurian members of the Moffat Series, as there is between the corresponding formations in the Girvan area.

The uppermost five zones of the Caradoc and Ashgill series (p. 13) are recognized in the Hartfell Shales of the Central Belt. The zones are characterized by the species shown below, in addition to the zone-fossil itself:

Dicellograptus anceps:	*Climacograptus supernus, Orthograptus truncatus abbreviatus.*
Dicellograptus complanatus:	*C. miserabilis, O. truncatus socialis.*
Pleurograptus linearis:	*Amphigraptus divergens, C. styloideus, C. tubuliferus, Dicellograptus elegans, Leptograptus capillaris, L. flaccidus, Neurograptus fibratus, O. quadrimucronatus.*
Dicranograptus clingani:	*A. radiatus, C. caudatus, Corynoides calycularis, D. morrisi, D. caduceus, D. forchhammeri, Dicranograptus ramosus, L. flaccidus, N. margaritatus, O. calcaratus, O. truncatus truncatus, Hyalostelia fasciculus.*

Climacograptus wilsoni: *'Buthograptus laxus', Climacograptus bicornis, D. nicholsoni, D. ramosus. Glossograptus hincksi, O. vulgatus.*

Sections similar to that at Hartfell Spa, in which the Hartfell Shales occur between the Glenkiln and Birkhill shales, occur in most of the outcrops to the north-east, as, for example, at Dobb's Linn, Craigmichan Scaurs, and Mountbenger. In the Selkirk–Melrose area the Hartfell Shales are the oldest rocks exposed, but their base must be nearly reached at Lindean, between these towns, where the problematical '*Buthograptus laxus*,' confined to the Zone of *C. wilsoni*, has been recorded. The Zone of *P. linearis* is recognized at Leaderfoot Bridge, near Melrose, and Lower Hartfell graptolites are present in the most north-easterly exposure, near Lauder.

South-westwards from Moffat the Hartfell Shales occur wherever the Glenkiln Shales are found. Peach and Horne described several localities rich in graptolites in streams between Dumfries, New Galloway, and Kirkcudbright. Farther west good sections in fossiliferous black shales occur in the Cree north of Newton Stewart, some 11 km south-east of Glenluce, and at Clanyard Bay near the Mull of Galloway.

Towards the north-west, along the southern edge of the Northern Belt, the outcrops of the Lower Hartfell Shales are in many cases similar to those of the Moffat area. For example at Morroch Bay, south of Portpatrick, some 18 m of shales at the top of the Kirkcolm Group yield an abundant graptolite fauna of Upper Glenkiln or Lower Hartfell age, but higher beds of the Lower Hartfell consist of thick greywackes with graptolite shales. When the outcrops are traced farther to the north-west, however, the change to a greywacke succession, in which the graptolites are confined to interbedded thin bands of black shale, is seen to affect the lower beds as well. The temporary development in the Northern Belt of neritic conditions, which prevailed in the Girvan area, is indicated by the occurrence of impure limestones and conglomerates with a shelly fauna including trilobites. The lateral change in lithology is similar to that described above in the Glenkiln Shales, the rocks becoming coarser-grained and thicker towards the north-west, but it takes place farther south in the Hartfell rocks than in the Glenkiln. Largely because of the coarser nature of the sediment not all the graptolite zones of the typical Hartfell Shales have been recognized in the Northern Belt. The transitional fauna at the base of the formation at Morroch Bay implies the presence of the Zone of *C. wilsoni* but this zone has not been proved elsewhere. Younger rocks in this area form the Portpatrick Group of Kelling, extending from the Lower Hartfell possibly to the Silurian. The group is some 1200 m thick and consists of greywackes with thick bands of bluish black shale. The topmost Zone of *D. anceps* may however be completely absent in the Northern Belt, the youngest rocks present belonging to the underlying Zone of *D. complanatus*, which is rare in north-eastern districts but has been recorded on the northern slope of the Lammermuir Hills south of Stenton. Near Abington the Lowther Shales are regarded as being of Upper Hartfell age. They are grey and blue shales associated with greywackes and pebbly grits, estimated by Peach and Horne to be about 250 m thick. There are also a few thin ribs of limestone associated with calcareous grits yielding traces of fossils.

Between the Nith and the Clyde a coarse conglomerate has been taken as the base of the Hartfell and a similar bed, probably on the same horizon,

occurs in the Shinnel and Chanlock waters, north of Moniaive, in the hills near Carsphairn, and in the Afton Water. The pebbles consist of gabbro, granite, felsite, lava, chert, greywacke, black shale and quartzite. In the Glenaylmer Burn, north of Sanquhar, the conglomerate rests unconformably on radiolarian chert, and includes blocks of lava up to 0·6 m across. Correlation with the Benan Conglomerate of the Girvan area is suggested by the similarity of the constituent pebbles. A pebbly grit known as Haggis Rock may locally occupy this stratigraphical position. It consists of small fragments of coloured chert and igneous rocks, in a matrix of igneous material, but the name has been applied to a number of different bands and no single stratigraphical connotation can be associated with it.

Fossiliferous conglomerates are associated with shales and grits at Duntercleuch, Snar, Wallace's Cast, and Kilbucho, in the ground between Sanquhar and Peebles. Fossils from these localities include *Christiania tenuicincta*, *Rafinesquina deltoidea*, *Strophomena kilbuchoensis*, and species of *calymenid*, *cheirurid*, *homalonotid*, *phacopid*, *remopleuridid*, and *trinucleid* genera. It is not known whether or not the conglomerates lie on one stratigraphical level.

The Wrae Limestone and its associated conglomerates and contemporaneous volcanic rocks were formerly regarded as being of Upper Hartfell age. The limestone occurs as a volcanic breccia within a band of tuff, and at Wrae, Glencotho, Drumelzier, and Winkston, to the west and north of Peebles, has yielded a fauna which includes corals, crinoids, brachiopods, and trilobites. Graptolites from a higher horizon in the tuff, and those just above, in the Stobo Slates, are indicative of a position high in the Lower Hartfell Zone of *D. clingani*, but conodonts from the Limestone have recently been said to be of pre-Caradoc aspect.

In the Rhins of Galloway Kelling divided the Hartfell rocks into two groups, of which the more northerly and more generally arenaceous Galdenoch Group is regarded as correlative with the lower part of the Portpatrick Group. This correlation is supported by consideration of the rock fragments in the greywackes. Greywackes and shales of the Portpatrick Group extend southward to the boundary with the Silurian rocks of the Centra lBelt. They include occasional inliers of Hartfell and Glenkiln shales, generally seen to be faulted on their southern sides, and young fairly consistently towards the north, as do the adjacent Silurian rocks. This evidence requires that the Ordovician–Silurian boundary is a fault with large downthrow to the south. North of Portpatrick a similar parallel fault is thought to separate the Portpatrick and Kirkcolm groups. Visible shearing suggests that both are reverse-faults with a rather low dip towards the north.

Volcanic Rocks of Glenkiln and Hartfell Age

The work of Walton and Kelling on the coast between Ballantrae and the Mull of Galloway has shown that spilitic lavas are developed at several horizons in the Glenkiln rocks, where they were formerly regarded as fold-repeated occurrences of one volcanic episode. It is probable that many of the other occurrences of lava in the Northern Belt previously assigned to this one Glenkiln episode, or to another in the Zone of *D. clingani*, were in fact extruded during a larger number of separate episodes. Reference has been made (p. 18) to the indications that many of the lavas formerly thought to be

of Arenig age are now considered to be Llandeilian, and in general terms the Glenkiln Shales are seen to be much more closely linked to underlying lavas and cherts than was formerly supposed. In the Central Belt fine tuffs are interbedded with the Glenkiln Shales at several localities, for instance at Dobb's Linn, and at Trowdale, near Castle Douglas, and probably represent wind-blown volcanic dust.

The Glenkiln volcanic rocks are present in many localities in the Northern Belt, extending from the Rhins of Galloway to beyond Gala Water, and are best displayed in the neighbourhood of Bail Hill, near Sanquhar. Mrs. Eyles[1] showed that they are there younger than shales with Upper Glenkiln graptolites. The lavas and minor intrusions commonly have dioritic affinities and among the pyroclastic rocks, which are more abundant, is the unusual augite-tuff first described by Teall. This rock, with large crystals of augite, often unbroken, was thought by Mrs. Eyles to be an auto-brecciated basalt. The whole complex was regarded as a denuded volcanic pile, the vent being marked by a central area of coarse agglomerate containing a variety of rocks not known at outcrop in the vicinity, such as a soda-syenite. Mrs. Eyles confirmed Teall's observation of the similarity of the tuffs to those in other areas, particularly to the augite-andesite-tuff of Mains Hill, near Ballantrae, later examined by Pringle and thought to be possibly of Glenkiln age. To the same period may be referred the tuffs and breccias which are found in the area between the Euchan and Kells waters, near Sanquhar, and said by Eckford to be closely associated in the Poltallen Burn with shales yielding Glenkiln graptolites. In the Rhins of Galloway agglomerate and spilite at Broadsea Bay were described by Peach and Horne as of Upper Glenkiln age, and Pringle suggested they be correlated with the Bail Hill volcanics. Kelling however thinks that they lie in the basal Glenkiln Zone of *Nemagraptus gracilis*.

Biotite-hornblende-andesite is exposed at several points between Bail Hill and Coulter, in the Clyde Valley. A short distance south of Coulter there are one or two beds of augitic ash which closely resemble the tuffs of Bail Hill. The pyroclastic rocks are perhaps not more than 15 m thick and are associated with shales which have yielded a Glenkiln fauna. Lavas in the Hope Burn, near Heriot, are now believed to be of Glenkiln age, rather than Arenigian.

The Hartfell volcanic rocks are restricted to the valley of the Tweed in Peeblesshire. They were originally assigned to the Upper Hartfell, but Eckford and Ritchie proved that they lie in the Lower Hartfell Zone of *D. clingani*. The lavas are exposed at many localities between Winkston Hill, 3 km north of Peebles, and Glencotho, some 23 km to the south-west, and are associated with tuff, limestone-breccias, grits, cherts, and shales. At Winkston Hill they are at least 30 m thick but thin rapidly towards the south-west. At Wrae Hill, 16 km south-west of Peebles, the lower lava, 5 m thick, is succeeded by some 20 m of greenish calcareous tuff and tuffaceous grit. This is full of blocks of trachytic lava and contains two flows of similar rock as well as, at a higher level, the Wrae Limestone (p. 24). Lower Hartfell graptolites occur some 2 m below the top of the tuffaceous grit at Stobo. The overlying Stobo Slates are about 90 or 120 m thick. The lavas are described as quartz-keratophyre and soda-trachyte, banded and perlitic forms

[1] More detailed notes by Mrs. Eyles are quoted in earlier editions of this publication.

occurring near Peebles, and are regarded as local varieties of the same spilitic suite as the Arenig and other earlier Ordovician lavas of southern Scotland.

Caradoc and Ashgill Rocks: Girvan Area

In the Girvan area the rocks coeval with the Glenkiln and Hartfell shales form respectively the Barr and Ardmillan series. The **Barr Series** is of variable constitution and thickness. A characteristic section, given below, is exposed in the Benan Burn, about 2 km west of Traboyack (Fig. 3). The stratigraphy of the Series, and of the lower part of the Ardmillan Series, has recently been studied by Williams, to whom much of the detail in this account is due.

	metres
Benan Conglomerate	over 30
Didymograptus superstes Mudstones: grits and conglomerates; siltstones, pebbly mudstones, and greywackes; calcareous siltstones and mudstones	40
Stinchar Limestone: thickly bedded limestones, platy above; rubbly fine-grained limestones	60
Valcourea confinis Flags: fine-grained calcareous platy sandstones, coarser-grained and more massive downwards	45
Gap	34
Kirkland Conglomerate: current-bedded calcareous pebbly grits	6
massive conglomerate	12
(seen nearby to be at least 240 m thick)	

The Series was laid down upon an irregular surface composed mainly of members of the Ballantrae Igneous Complex and the age of the earliest rocks differs widely over the area. For example, the Kirkland Conglomerate occurs only on the south-eastern side of Benan Hill, whereas on the eastern slopes of Aldons Hill the oldest rocks are conglomerates of Stinchar Limestone age. There is also considerable evidence of lateral change of facies and of local erosion during the period of deposition. Thus the Stinchar Limestone thins from 60 m to 18 m between the Benan Burn and Auchensoul, less than 2·5 km to the north-east. The upper part of the limestone of Benan Burn is represented near Auchensoul by conglomerate, with brachiopod and crinoid fragments, and the *D. superstes* Mudstones by a more calcareous rock attenuated by erosion prior to the deposition of the Benan Conglomerate. An additional limestone, formerly thought to be the Stinchar Limestone, is developed at Auchensoul below the *V. confinis* Flags. It is of variable thickness up to 18 m. Some 3 km to the north, near Brockloch, the Stinchar Limestone lithology extends upwards into the Benan Conglomerate and downwards into the *V. confinis* Flags.

The most notable examples of contemporaneous erosion are afforded by the Benan Conglomerate which cuts down into the Stinchar Limestone in a channel less than 1·5 km wide south-west of Benan Hill, and cuts rapidly across the whole of the Barr Series east of Aldons Hill to rest directly on the igneous basement.

The Kirkland and Benan conglomerates are similar in their content of pebbles and boulders, which are mainly of local rocks but include some of unknown origin such as a red granite. The sandy matrix is characteristically

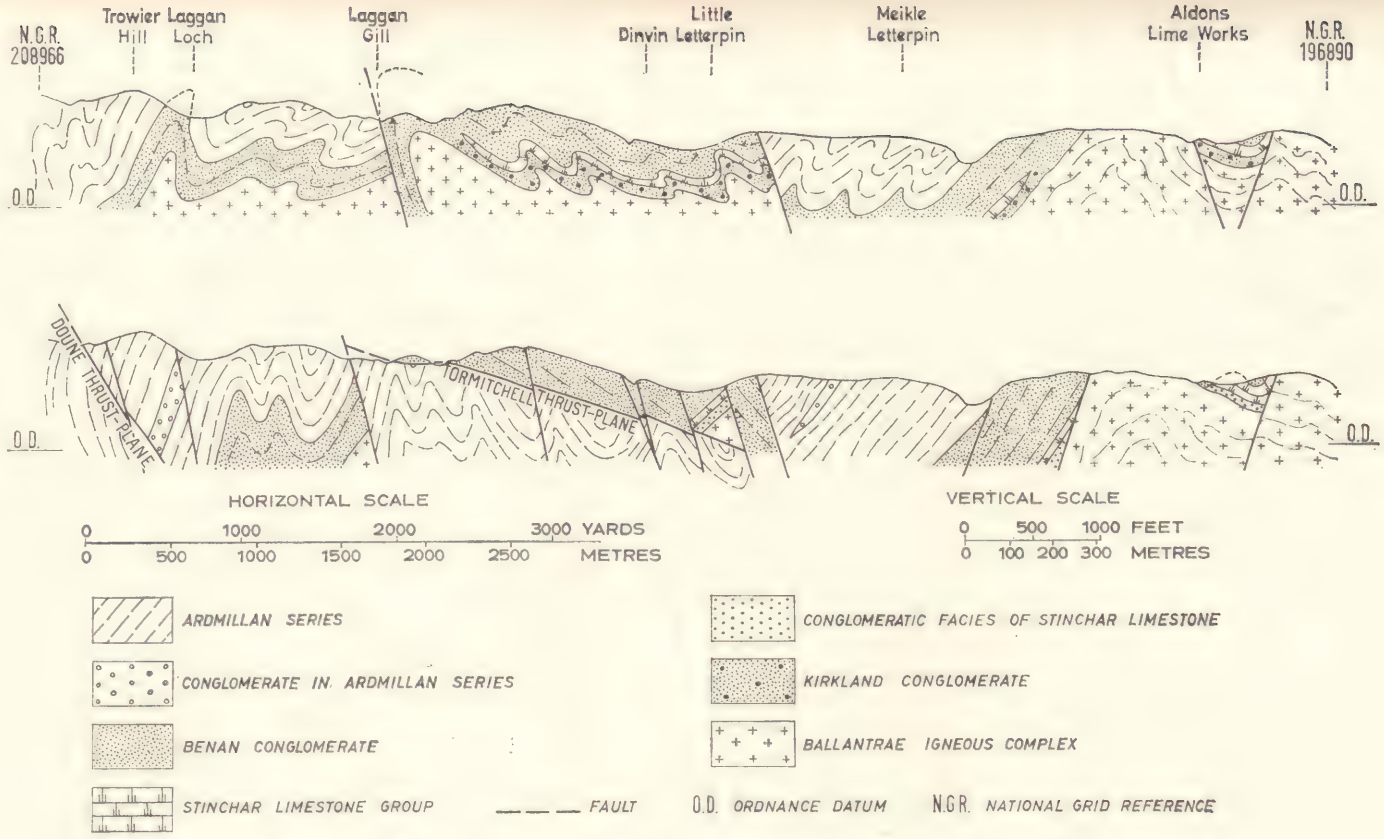


FIG. 6. *Alternative interpretations of Ordovician structure and stratigraphy in the Girvan area*
(Based on the work of Peach and Horne 1899 (above) and Williams 1962 (below).)

purple in the Kirkland Conglomerate and dark grey or green in the Benan. The Benan Conglomerate includes thin mudstones and siltstones in the Stinchar valley, and *Leptellina semilunata* and crinoid stems, its only fossils, have been found in its lower beds. Facies changes and differential down-cutting account for considerable variations in the thickness of the Benan Conglomerate, from a maximum of 640 m in the Stinchar and Assel valleys to not more than 90 m on the north-western limb of the Aldons Hill anticline. In the Benan Hill syncline, where no younger rocks are preserved, thicknesses of 500 to 600 m are recorded. Williams' recent work has shown that the Benan Conglomerate is less tightly folded and accordingly thicker than was formerly supposed. The Barr Series was thought by Peach and Horne to be altogether about 250 m thick, whereas the incomplete succession between the Stinchar and Benan Hill appears to reach about 900 m.

The Stinchar Limestone is worked in extensive quarries at Tormitchell, where it has been thrust from the south-east over Ardwell greywackes. At least 50 m thick, the Limestone occurs in several lithological types ranging in grain-size from muddy to pebbly, oolitic in some bands, elsewhere crinoidal or shelly, and variously massive, nodular, or platy. The underlying calcareous grit and breccia of igneous rocks are probably to be correlated partly with the Limestone of Benan Burn and partly with the *V. confinis* Flags.

The three formations between the conglomerates contain an abundant and varied fauna, largely of neritic forms. Brachiopods and trilobites are the more significant common groups. A diagnostic gastropod is *Maclurea logani*, and the limestones contain *Girvanella* and *Saccamminopsis* in abundance. The occurrence in certain mudstones of the graptolite genera *Climacograptus*, *Cryptograptus*, *Dicranograptus*, and *Diplograptus* is of essential importance in the correlation of the Barr Series with the Glenkiln Shales of the Moffat succession.

Williams divides the brachiopod fauna of the Barr Series into two groups, occurring below and above the middle of the Stinchar Limestone, and Tripp draws a similar distinction between the trilobites of these beds. Over half the brachiopod species, including *Bimuria* cf. *buttsi*, *Leptellina semilunata*, *Orthambonites parvicrassicostatus*, *Phragmorthis buttsi*, and *Ptychoglyptus* cf. *virginiensis*, occur in both groups. *Hesperorthis australis exitis*, *Macrocoelia macallumi*, *Multicostella* aff. *plena*, and *Valcourea* [*Orthis*] *confinis* are restricted to the lower division, but the first reappears in the Balclatchie Group. The new stocks appearing in the upper division include *Craspedelia* cf. *marginata*, *Eremotoechia silicica*, *Scaphorthis* cf. *virginiensis*, and *Taphrorthis sp.* Of the thirty-three trilobite genera in the upper division sixteen are unknown in the lower. Tripp's work, coupled with the earlier comprehensive studies of Reed, shows that the trilobite fauna of the Barr Series comprises over fifty genera. Common forms include species of *Bartoninus*, *Bronteopsis*, *Bumastoides*, *Calliops*, *Encrinuroides*, *Illaenus*, *Raymondaspis*, *Remopleurides*, and *Sphaerexochus*.

The brachiopod and trilobite assemblages show much more resemblance to those of North America and Scandinavia than to those of other parts of Britain. Thus the trilobite species of the *V. confinis* Flags occur only in the Girvan area, but more of the genera are known from the Lower Edinburg formation of the Appalachians than from other British areas. Nine of them occur also in older American rocks but there is no link with older rocks in Britain.

The Ordovician conglomerates of the Girvan area have been described by Kuenen and Williams as slide-conglomerates, deposited against steep submarine slopes which were probably fault-planes, in such a way as to tend to remove the topographic irregularity arising from repeated movement of the faults. The northern limits of the Kirkland and Kilranny (p. 30) conglomerates, for example, are formed by such faults, trending eastward or east-north-eastward and with southward downthrow, and the variable thickness of the Benan Conglomerate is also in part due to them. By this hypothesis the detrital rocks of the Stinchar and Craighead (p. 31) groups were laid down in the shallower water to the north of the faults, and the greywacke associations of the Tappins (p. 19), Balclatchie, and Ardwell groups in the deeper water beyond the reach of the sliding conglomerates.

Hubert, on the other hand, regards the Kilranny Conglomerate as having been laid down gradually by strong bottom-currents, probably in quite shallow water. The younger Ardmillan rocks are thought to have been similarly formed, the bottom-currents having flowed south-eastwards, in contrast to the south-westward flow of Kilranny times. The upper beds of the Whitehouse Group (p. 31) are interpreted as the sediments of a delta spreading out from the north-west.

The rocks of the **Ardmillan Series** are not markedly different from the Hartfell rocks of the Northern Belt, but their thickness, which is probably considerably in excess of 2000 m, is much greater. The five groups which constitute the Series were recognized by Lapworth.

		metres
Drummuck Group	Mudstones, calcareous sandstones Sandstones and grits	120
Shalloch (Barren) Flagstone Group	Flagstones, shales, mudstones	240
Whitehouse Group	Soft green mudstones and grey flagstones with ribs of limestone. Thin band of conglomerate at base. Grey and green shales.	90
Ardwell Group	Grits, greywackes, siltstones, and mudstones, with bands of conglomerate and lenticular pebbly grit.	1200
Balclatchie Group	Calcareous conglomerates, grits, and sandstones. Calcareous mudstones. Conglomerates and grits. Grits, greywackes, siltstones, and mudstones.	300

The thicknesses of the Balclatchie and Ardwell groups are based on the recent work of Williams and are altogether nearly four times the figure given by Lapworth, whose estimates for the other three groups are given above. No later independent figures for these higher groups have been published.

The Balclatchie Group is typically exposed in Penwhapple Burn, some 3 km north-west of Barr. The base is not seen, the lowest rock being the Doon Hill Conglomerate, formerly regarded as part of the Benan but now considered to lie at least 9 m above it. The succeeding Balclatchie Mudstones, dark green and calcareous, and at least 25 m thick, have yielded over 100 species of fossils from a roadside exposure near 'Balclatchie Bridge', south

of Green Hill. These include the sponge *Nidulites favus*, the graptolites *Dicranograptus tardiusculus* and *Orthograptus apiculatus*, and the brachiopods *Glyptomena girvanensis*, *Glyptorthis balclatchiensis*, and *Leptellina llandeiloensis*. Trilobites are remarkably abundant and include several species of *Amphilichas*, *Ampyx*, *Diacanthaspis*, *Illaenus*, *Proetus*, and *Remopleurides*. At the top of the Group is the Balclatchie Conglomerate, a calcareous fossiliferous rock about 30 m thick. Farther to the south-west the Group includes several conglomerates, some now correlated with that of Doon Hill, but locally it consists mainly of massive greywackes and mudstones.

In the Laggan Burn, south-east of Girvan, Balclatchie mudstones contain limestone nodules with an abundance of well-preserved graptolites. The fauna, described by Bulman, includes *Climacograptus brevis*, *C. scharenbergi*, *Cryptograptus tricornis*, *Dicranograptus nicholsoni*, *Diplograptus lepthotheca*, and *Orthograptus apiculatus*, and is indicative of a horizon close to the Glenkiln–Hartfell boundary.

The well-known occurrence of 'Benan Conglomerate' on the shore at Kennedy's Pass (Fig. 3) is believed by Williams to be of a Balclatchie formation which he has called the Kilranny Conglomerate. This rock is about 150 m thick and its base is thought to lie some 90 to 150 m above the top of the Benan. It is seen in places as far north as the latitude of Woodland Bay. The beds above it belong by original definition to the Ardwell Group, but near Ardwell and on Ardmillan Braes they contain a rich fauna like that of the Balclatchie Mudstones.

Greywackes of the Ardwell Group are typically exposed on the shore north of Kennedy's Pass, but the succession here is incomplete and complicated by folds and faults. Williams has recorded a succession through the Group in the ground north-east of Tormitchell, which may be abbreviated as follows:

		metres
Cascade Grits and Conglomerates	at least	120
Grits, greywackes, and mudstones	about	600
Assel Conglomerate		70
Grits, greywackes, and mudstones, fossiliferous near base		135
Tormitchell Conglomerate (Barbae Grits of Lapworth)		90
Sandstones, siltstones, and mudstones, with lenses of fossiliferous grit in lower beds		195

Of the named conglomerates the Assel band is of much more restricted development than the other two. The conglomerates and grits are variably fossiliferous, the fauna including algal and bryozoan nodules and corals in addition to the abundant brachiopods and trilobites. The most valuable fossiliferous horizon is just above the Tormitchell Conglomerate.

The Group occurs also in a number of areas between Camregan Hill and Aldons Hill, and in a narrow inlier running north-east to Delamford, 5·5 km north-north-east of Barr. The thickness does not reach the 1200 m recorded near Tormitchell but many of the local successions are incomplete. Brachiopods and graptolites permit stratigraphical comparison between several of the outcrops. Secondary cementstone nodules occur locally, especially in the lower rocks, but conglomerates are in general poorly developed, or ill exposed, except in Penwhapple Burn.

On Ardwell shore the Ardwell Group consists of greywackes, siltstones, and mudstones, with some massive pebbly grits and nodules and thin bands of cementstone. About 500 m of rock is exposed, but the section is fault-bounded above and below and the full thickness in this area is estimated to be of the order of 1100 m.

Graptolites from the Ardwell Group include *Climacograptus bicornis*, *C. caudatus*, *C. scharenbergi*, *Corynoides calycularis*, *Dicellograptus forchhammeri*, *Dicranograptus ramosus*, *Neurograptus margaritatus*, and *Orthograptus apiculatus*, indicative of horizons low in the Hartfell Shales. Many of the brachiopod species are the same as in the Balclatchie Group but an important new form is *Reuschella* cf. *americana*. The Balclatchie–Ardwell brachiopods, like those of the Barr Series, are more readily compared with those of the Appalachians than with those of other parts of Britain, and a correlation has been established between these Girvan groups and the middle and upper parts of the American Edinburg (Porterfield–Wilderness) formation.

The Craighead Limestone is the oldest member of the Caradoc Series in the Craighead Inlier, which lies on the northern side of the Girvan Valley to the west of Dailly. In the Craighead quarries it is seen to consist of a variable succession, up to about 90 m thick, of sandy limestones and calcareous mudstones overlapping across an uneven floor of Llandeilian cherts and spilites. The basal deposit is often seen to be a dark green spilitic conglomerate. Algae of the genus *Girvanella* and corals form the framework of the sediment, and the rich fauna also includes several forms of graptolites, crinoids, annelids, brachiopods, molluscs, and trilobites. Lapworth and Peach and Horne correlated the Limestone with the Stinchar but subsequent work placed it in the Balclatchie Group, although retaining it and the succeeding Plantinhead Flagstones in the Barr Series.

Recent research work by Tripp on the trilobites has shown however that the fauna, which includes such species as *Achatella consobrina*, *Encrinurus praecursor*, *Flexicalymene shirleyi*, and *Otarion beggi*, is more like that of the Drummuck Group than that of the Balclatchie. Williams' study of the brachiopods points to a correlation with a horizon slightly below that of the Cascade Grits. The Craighead Limestone is thus considered to be post-Balclatchie, probably high in the Ardwell Group, or even higher within the Ordovician.

The boundary between the divisions of the Whitehouse Group established by Lapworth (p. 29) is taken as the boundary between the Caradoc and Ashgill series. The highly inclined beds of the lower division occupy the shore northwards from Ardwell Bay and have yielded *Dicellograptus forchhammeri* and several species of brachiopod. Members of the upper division are visible at low tide to the west of Ardmillan House, their lowest beds distinguished by the occurrence of a band of bright purple mudstone. Highly fossiliferous calcareous grits and shales lie above. This division can be followed northeastwards to Woodland Bay, but the inter-relationships of the strata are complicated by inversion and folding. Further subdivision was however made in Woodland Bay by Lapworth. At the base is a band 1·5 m thick, predominantly of black shale, yielding amongst others the zone fossil *Dicellograptus complanatus*, and this is succeeded by 3 m of hard flaggy shales with grey calcareous ribs and in some bands an abundance of specimens of

Dictyonema. About 2 m of highly calcareous sandstones form the topmost member, the *Dionide* Beds. Other characteristic fossils from this locality include *Nematolites*, *Halysites catenularia*, *Leptellina albida*, *Strophomena shallochensis*, *Tentaculites anglicus*, and many gastropods and cephalopods. The trilobites include *Corrugatagnostus sp.*, *Dionide lapworthi*, *Illaenus shallochensis*, *Stygina latifrons*, *Symphysops subarmatus*, and *Telephina reedi*.

Lapworth recorded nearby the presence of graptolites of the highest Caradoc Zone of *Pleurograptus linearis*. These include *Climacograptus tubuliferus*, *Dicellograptus morrisi*, *Leptograptus flaccidus*, *Orthograptus quadrimucronatus*, and *P. linearis*. In the Barr area a similar fauna was obtained by him from the lower division in Penwhapple Burn.

The Whitehouse Group is succeeded by the Shalloch (or Barren) Flagstone Group, a series of almost unfossiliferous flagstones and shales with bands of greywacke. They are best exposed in Woodland Bay, and are also seen in Penwhapple Burn in a section 1200 m in length. In this section the beds have an inverted dip to the south-east, apparently running under the Whitehouse Group, and are faulted to the north-west against Silurian rocks. Green mudstones near the base of the Group have yielded, in Penwhapple Burn, the characteristic trace-fossil *Nematolites*.

In the Craighead Inlier the Craighead Limestone and Plantinhead Flagstones, of upper Ardwell age, are succeeded by rapidly alternating sandy and shaly rocks typical of the Ardwell, Whitehouse, and Shalloch Flagstone groups. The only fossils seen, however, are forms such as *Nematolites*, characteristic of the Shalloch Flagstones, and there is no evidence of the presence here of the Whitehouse Group. The inlier has an anticlinal form with north-eastward plunge.

The Drummuck Group occurs only in the Craighead Inlier. It consists mainly of mudstones, with sandy beds and, in places, a basal conglomerate or grit. Lamont has divided the Group into two parts distinguished by their brachiopod and trilobite faunas. On Quarrel Hill olive-green mudstones low in the Group have yielded many trilobites, including *Cryptolithus portlockii girvanensis*, *Flexicalymene* cf. *meeki*, *Lonchodomas drummuckensis*, *Pterygometopus*? *quarrelensis*, and a variety of *Tretaspis seticornis*. Brachiopods are more abundant in the succeeding 'Crinoid Bed', a shelly sandstone, the most common species being *Brachyprion matutinum* and *Fardenia scotica*, both unknown in the upper division. Other forms confined to the lower division are *Leangella discuneata*, *Nicolella actoniae* var., and *Sowerbyella subcorrugata*. Gastropods and bivalves are also common.

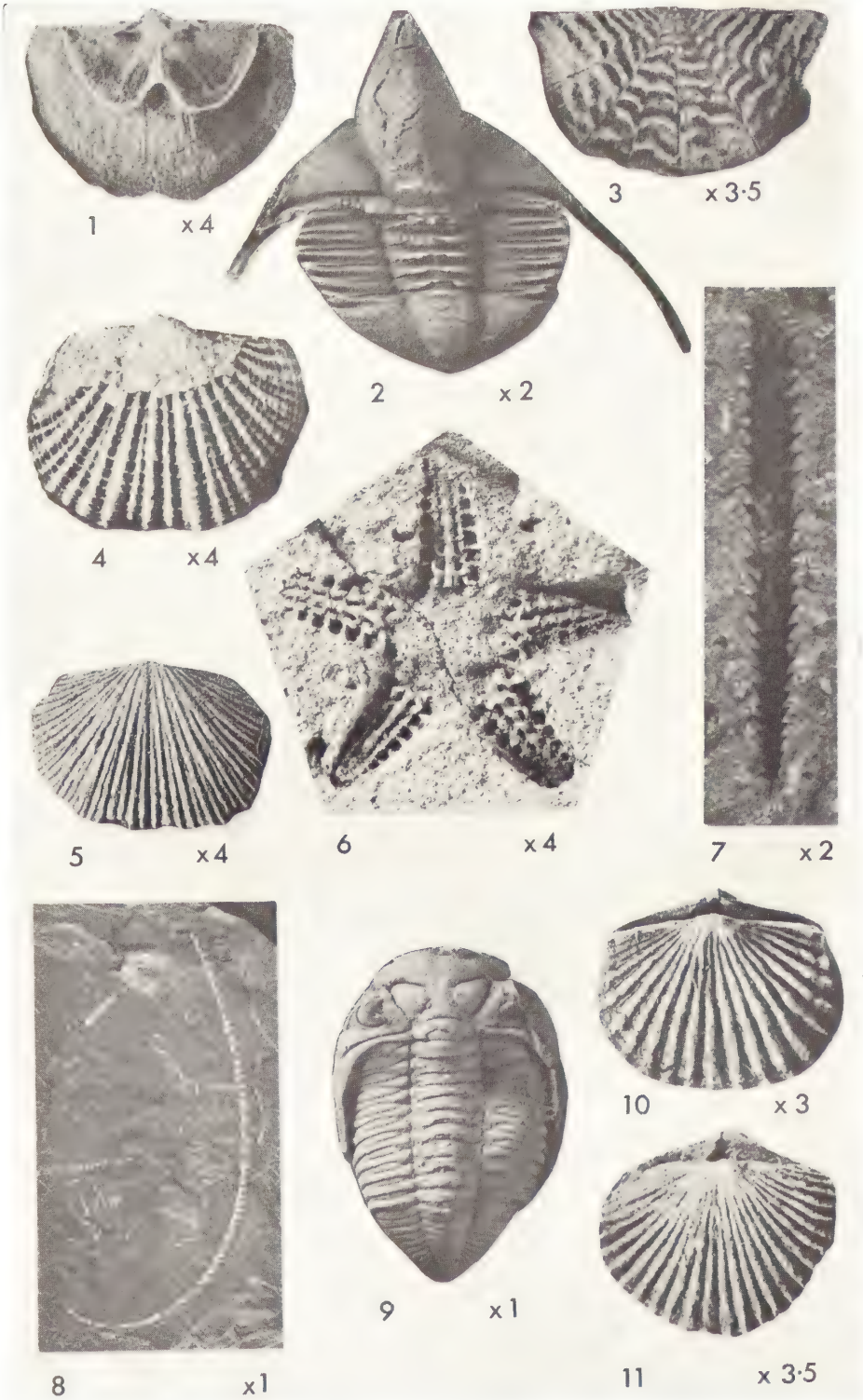
PLATE II

A. Pillow-lavas of Arenig age near Downan Point, Ayrshire, showing vesicular margins. The interstices are filled with limestone and chert, and the pillows are smoothed by modern wave action. (Geol. Surv. Photo. No. C706).

B. Folded Silurian rocks at Pettico Wick, near St. Abbs, Berwickshire. A broad horizontal syncline in greywackes and shales. The complex axial region of the fold forms the low rocks near water-level. The crag in the right foreground is of Lower Old Red Sandstone lava which forms the peninsula of St. Abb's Head, separated from the Silurian rocks by a fault in the bay. (Geol. Surv. Photo. No. D1230).

A

B


1 x 4
2 x 2
3 x 3·5
4 x 4
5 x 4
6 x 4
7 x 2
8 x 1
9 x 1
10 x 3
11 x 3·5

The higher division is well exposed in the Lady Burn near South Threave. The highly fossiliferous 'Starfish Bed' is a hard greenish grey calcareous sandstone rich in cystoids, asteroids, brachiopods, molluscs, and tribolites. Over thirty genera of trilobites have been recorded. They are grouped in the Zone of *Phillipsinella parabola*, which has been equated to that of *Dicellograptus complanatus*, and include *Bartoninus keisleyensis*, *Diacalymene drummuckensis*, and *Sphaerocoryphe thomsoni*, as well as *P. parabola*. *Dicellograptus anceps*, of the highest Ordovician zone, has been recorded in mudstones above the 'Starfish Bed' in the Lady Burn. The highest beds are sandy mudstones rich in trilobites, brachiopods, and molluscs, and are also referred to the Zone of *D. anceps*. Higher Ashgill beds may be cut out by an unconformity at the base of the Silurian, but may be represented by the High Mains sandstone (p. 45).

The Drummuck trilobite fauna, like those of older Ordovician formations, includes a high proportion of forms peculiar to the Girvan area.

PLATE III

LOWER PALAEOZOIC FOSSILS

1. *Leptellina semilunata* Williams. Ordovician, Stinchar Limestone.
2. *Lonchodomas drummuckensis* Reed. Ordovician, Drummuck Group, Starfish Bed.
3. *Ptychoglyptus* cf. *virginiensis* Willard. Ordovician, Albany Division, Tappins Group.
4. *Glyptorthis balclatchiensis* (Davidson). Ordovician, Craighead Limestone.
5. *Scaphorthis* cf. *virginiensis* Cooper. Ordovician, Stinchar Limestone.
6. Starfish. Ordovician, Drummuck Group, Starfish Bed.
7. *Orthograptus rugosus* (Emmons) *apiculatus* Elles and Wood. Ordovician, Ardwell Group.
8. *Monograptus communis* (Lapworth) *rostratus* Elles and Wood. Silurian, Birkhill Shales.
9. *Chasmops bisseti* (Reed). Ordovician, Drummuck Group.
10. *Orthambonites parvicrassicostatus* Cooper. Ordovician, Stinchar Limestone.
11. *Hesperorthis australis* Cooper *exitis* Williams. Ordovician, *Valcourea confinis* Flags.

Nos. 1, 3, 4, 5, 10 and 11 are reproduced by permission of the Geological Society of London from:

Williams A. 1962. The Barr and Lower Ardmillan Series (Caradoc) of the Girvan district, south-west Ayrshire. *Mem. geol. Soc. Lond.*, 3.

4. SILURIAN

More than half of the area of the South of Scotland is occupied by Silurian rocks, which crop out in a belt up to about 50 km wide to the south-east of the Ordovician. The belt extends from the Mull of Galloway to the North Sea, but in the east the outcrop is much interrupted by areas of Upper Palaeozoic rocks. There are also small areas of Silurian to the north of the Ordovician of Girvan.

Llandovery rocks, the oldest of the Silurian system, form the 'Central Belt' of Peach and Horne, by far the greater part of the main outcrop, lying between Ordovician rocks to the north-west and younger Silurian, of the Wenlock Series, to the south-east. These last constitute the narrow 'Southern Belt', which extends from Burrow Head to near Hawick, east of which rocks of the same age occur in a number of large inliers surrounded by Upper Palaeozoic strata. As pointed out in Chapter 2 the Silurian rocks are highly folded and their outcrop is modified in many places by the presence of Ordovician inliers.

			Graptolite Zones
Wenlock Series	Raeberry Castle Beds		*Cyrtograptus lundgreni* *C. ellesi* *C. linnarssoni* *C. rigidus*
	Riccarton Beds		*Monograptus riccartonensis* *C. murchisoni*
Llandovery Series	Gala Group	Hawick Rocks (unfossiliferous) Queensberry Grits Abbotsford Flags	*M. crenulatus* *M. griestoniensis* *M. crispus* *M. turriculatus*
	Birkhill Shales	Upper	*Rastrites maximus* *M. sedgwickii* *M. convolutus*
		Lower	*M. gregarius* *M. cyphus* *Cystograptus vesiculosus* *Akidograptus acuminatus* *Glyptograptus persculptus*

The subdivision and order of succession of the Silurian rocks of the Southern Uplands are controversial subjects. The classification shown opposite is based on the work of Lapworth and Peach and Horne, and also takes into account subsequent published research and changes in taxonomy.

The recognition of the lowest zone, which is about 1 m thick at the base of the Birkhill Shales at Dobb's Linn, is due to Jones and Pugh. The classification of the Wenlock Series requires complete revision as a result of recent research by Mrs. C. Clarkson, Craig, and Walton, which has confirmed the earlier view of the latter authors that the Raeberry Castle Beds in the type-area in Kirkcudbrightshire are of Llandovery age, and that the Hawick Rocks there are younger than the Riccarton Beds. The name 'Riccarton Group', used by Warren for all the Wenlock rocks of the Riccarton area in Roxburghshire, might appropriately be adopted for the Southern Uplands as a whole, and the term 'Raeberry Castle Beds' used only as a local name for Llandovery rocks near Raeberry Castle. It seems that the term 'Hawick Rocks' has been used in the past on a primarily lithological basis and may now be seen to be devoid of any precise age significance. In Kirkcudbrightshire and Roxburghshire evidence favours a Wenlockian age, but similar rocks in Wigtownshire have yielded Llandoverian graptolites (p. 41).

The subdivision of the Silurian rocks of the Girvan district, and their correlation with those of the Southern Uplands, were worked out by Lapworth and later slightly modified by Peach and Horne and by Pringle.

	Southern Uplands	Girvan District	
Wenlock Series	Raeberry Castle Beds		Dailly Series
	Riccarton Beds	Straiton Group	
Llandovery Series	Gala Group	Drumyork Group Bargany Group Penkill Group	
	Birkhill Shales	Camregan Group Saugh Hill Group Mulloch Hill Group	Newlands Series

The Newlands Series consists largely of shallow-water rocks with a fauna characterized by corals, brachiopods, molluscs, and trilobites. Graptolites occur in widely separated thin beds. The Series thus contrasts with the much thinner graptolitic Birkhill Shales in the same way as the varied Ordovician rocks of Girvan contrast with the Glenkiln and Hartfell shales of Moffat. Such differences are absent in the younger rocks, which in both areas include conglomerates, grits, greywackes, flaggy sandstones, shales, and mudstones, and are indeed more finely grained in the lower part of the Dailly Series than in the Gala Group. In this account the two areas are described separately.

Llandovery Rocks: Southern Uplands

The type-locality of the **Birkhill Shales** is Dobb's Linn, near Birkhill Cottage, at the head of Moffat Water (Fig. 7). Details of the rocks and of the graptolite sequence were first published by Lapworth in 1878, but those given here are based largely on the recent account by Toghill, which modifies only slightly Lapworth's original conclusions by the application of modern palaeontological and petrological knowledge.

The Lower Birkhill Shales, 20 m thick, consist largely of black graptolitic mudstone in bands between about 0·1 and 0·3 m thick. These bands are separated by partings of pale soft claystone, generally less than 0·1 m thick, which include occasional bands of grey calcareous nodules. The claystone is possibly of volcanic origin and is common also in the Upper Birkhill Shales, some 23 m thick, which are made up mainly of alternations of grey and black mudstone ranging from very thin layers up to beds about 0·3 m thick. Graptolites are abundant throughout and, although there is no apparent discontinuity at the base, there is a striking difference between the fauna and that of the underlying Upper Hartfell Shales. Lapworth observed that none of the many genera of many-branched graptolites of the Glenkiln and Hartfell shales survived in the Birkhill Shales. In contrast, except in the two lowest zones, there is in the Birkhill Shales a profusion of individuals and species of *Monograptus*, and, to a less extent, *Rastrites*, genera unknown in older rocks. The following list indicates the fossils characteristic of each graptolite zone at Dobb's Linn and neighbouring localities.

Rastrites maximus:	*Monograptus halli, M. nudus, M. turriculatus minor Petalograptus altissimus, R. maximus.*
Monograptus sedgwickii:	*Climacograptus scalaris, Glyptograptus tamariscus, M. decipiens, M. involutus, M. nudus, M. regularis, M. sedgwickii, M. tenuis, Discinocaris browniana.*
Monograptus convolutus:	*Cephalograptus cometa, Climacograptus scalaris. G. tamariscus, M. clingani, M. convolutus, M. denticulatus, M. jaculum, M. leptotheca, M. limatulus, M. lobiferus, Orthograptus bellulus, P. folium, R. hybridus, R. peregrinus.*
Monograptus gregarius:	*M. argutus, M. fimbriatus, M. gregarius, M. leptotheca, M. triangulatus, O. cyperoides, P. folium, R. peregrinus, D. browniana.*
Monograptus cyphus:	*Climacograptus innotatus, M. atavus, M. cyphus, M. revolutus, M. sandersoni, O. mutabilis, Rhaphidograptus toernquisti.*
Cystograptus vesiculosus:	*Climacograptus medius, C. rectangularis, Cystograptus vesiculosus, Dimorphograptus confertus, D. decussatus, D. elongatus, D. erectus, M. atavus.*
Akidograptus acuminatus:	*A. acuminatus, A. ascensus, Climacograptus normalis, Diplograptus modestus.*
Glyptograptus persculptus:	*C. medius, C. normalis, G. persculptus.*

The Llandovery outcrop was interpreted by Peach and Horne as being formed mainly by rocks of the Gala Group in which the Birkhill Shales were frequently exposed in narrow, tightly compressed anticlines. The recent re-

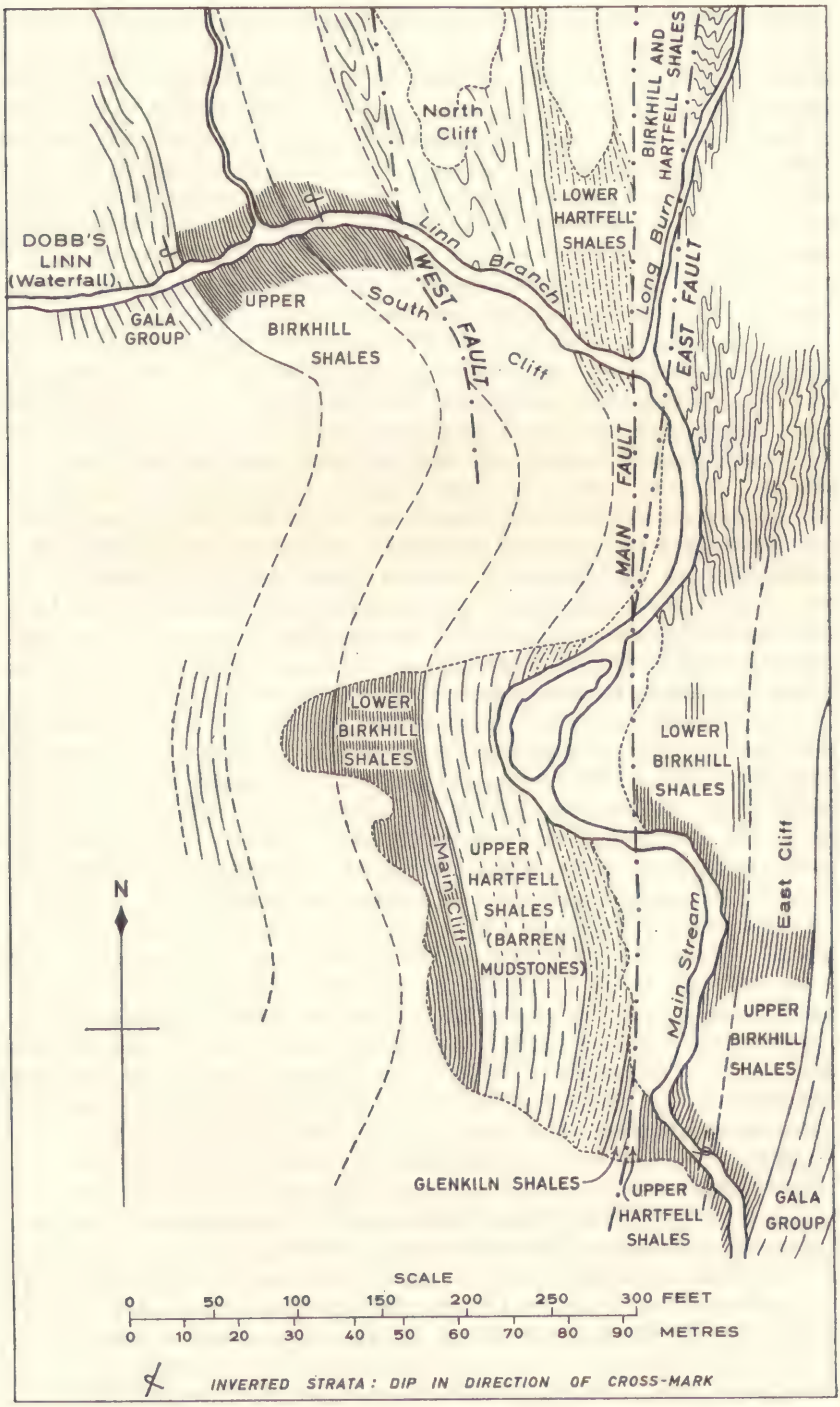


FIG. 7. *The Moffat Series at Dobb's Linn, Moffatdale*
(After Lapworth.)

interpretation of occurrences of the Glenkiln Shales in south-west Scotland (Figs. 4, 5) inspires doubt as to the fold-repeated nature of outcrops of the Birkhill Shales, such as those described by Peach and Horne at Clanyard Bay, near the Mull of Galloway, and in Selcoth Burn in Moffatdale. It may be that at these localities a number of bands of graptolitic shale are developed within a shale-greywacke sequence, as these authors themselves recognized elsewhere, for example near Slunkrainy, some 11 km north of Clanyard Bay. Positive evidence for this is given by recent work south of Glenluce in Wigtownshire. Such an interpretation is not necessarily inconsistent with the apparent facies change in the Shales as they are followed north-westwards from the Clanyard Bay–Moffat line (see below).

Little change is seen in the Birkhill Shales, even in minute details, as they are followed to north-east or south-west from Dobb's Linn, the characteristics of the type-section being maintained from the Mull of Galloway to Melrose. When they are followed across the strike, however, either to north-west or to south-east, changes in lithology and thickness occur within a very short distance. The onset of the greywacke facies, which characterizes the Gala Group, occurs generally earlier than along the 'Moffat Line' through Dobb's Linn. Black grits and greywackes appear in the Upper Birkhill Shales in the Entertrona Burn, in the upper Ettrick. At Ettrickbridge End, some 7 or 8 km south-east of the 'Moffat Line', greywackes and black shales make up the Lower Birkhill Shales, and the Upper consist of greywackes, flags, and shales, like those of the succeeding Abbotsford Flags. A similar change takes place to the north-west, for example in Peeblesshire and southern Midlothian. Near Fountainhall, some 16 km north-west of Galashiels, all the zones of the Birkhill Shales except the highest are represented by thin beds of graptolitic shale interstratified with conglomerates, grits, greywackes and sandy shales. Toghill points out that the highest graptolite shales are exposed at localities, such as Craigmichan Scaurs, a short distance south-east of the line through Dobb's Linn. These beds, higher in the Zone of *R. maximus*, yield specimens of *R. maximus* and *M. halli* in an abundance unknown at Dobb's Linn.

At Hartfell only the Zone of *R. maximus* is formed of massive grits, but at Newton Stewart the whole of the Birkhill Shales appears to consist of greywacke and shale. In the intervening ground the change in lithology is seen to be developed to a variable extent. The change is well displayed in the Galloway peninsula. At Clanyard Bay, as described above, the whole formation resembles equivalent beds at Dobb's Linn, but at Dumbreddan Bay, some 6 km to the north, the Zone of *M. sedgwickii* is represented by grey shales and limestone nodules, and farther to the north the change to coarser-grained sediments is developed in lower beds also.

Lithological variation of this type is not observed in the **Gala Group** which includes, in both the Southern Uplands and the Girvan area, flags, grits, greywackes and shales. Coarse-grained greywackes and conglomerates are common in the central region of the Central Belt. Peach and Horne estimated the maximum thickness of the Group to be between 900 and 1200 m whereas recent work in Wigtownshire and near Hawick suggests that in these areas the Hawick Rocks alone are at least 3000 m thick and the lower beds of the Gala Group at least 750 m. The difference is due to the realization that the beds are less tightly folded than was formerly thought, and is in accord with similar recent studies in the Ordovician rocks.

In the Moffat district the Gala Group is divided into three lithological formations:

Hawick Rocks	Grey, green, and red shales with brown flags and micaceous greywacke bands.
Queensberry Grits	Greywackes and shales with massive grits and bands of conglomerate.
Abbotsford Flags	Purple and grey flags and shales.

Three graptolite zones have been recognized, indicating the equivalence of the Group to part of the Upper Llandovery Series.

Monograptus griestoniensis	*M. griestoniensis*, *M. marri*, *Retiolites geinitzianus*, etc.
Monograptus crispus	*M. crispus*, *M. discus*, *M. exiguus*, *M. spiralis*, etc.
Monograptus turriculatus	*M. exiguus*, *M. galaensis*, *M. halli*, *M. turriculatus*, etc.

Grey shales at the base of the Group, and their junction with the Birkhill Shales, are well displayed at the waterfall at Dobb's Linn (Fig. 7). As the beds are followed towards the north the grey shale facies occurs progressively earlier, within the Birkhill Shales (p. 38). The main development of the Abbotsford Flags is in the ground between Moffat and Melrose, and the graptolites of the Zone of *M.turriculatus* have been found at several localities near Abbotsford.

In the Moffat area the Queensberry Grits are repeated by a series of overfolds inclined towards the north-west, the intensity of folding being sufficient to induce in places a schistose structure. The grit, which is locally conglomeratic, forms beds between 0·6 and 6 m thick. On Pin Stane hill, north-east of Beattock Summit, a bed which can be followed from the Clyde to the Tweed contains boulders up to 0·25 m across and rounded pebbles. They include Ordovician volcanic rocks, and metamorphic rocks like some from the Eastern Highlands. Shales between the grits yield the trace-fossils *Crossopodia scotica* and *Myrianites tenuis*.

In Wigtownshire and Kirkcudbrightshire, north-west of a line through Mochrum, Gatehouse of Fleet, and the northern edge of the Criffell Granite, the Llandovery outcrop is largely made up of Queensberry Grits, with local developments of Abbotsford Flags as on Culcaigrie Hill, east of Gatehouse, and in Trowdale Glen, north-east of Crossmichael. On Craigenputtock Hill, south of Moniaive, the Queensberry Grits include a conglomerate like that of Pin Stane, in that it contains pebbles of metamorphic Highland rocks second in abundance only to those of greywacke, which are up to 0·25 m across. The broad outcrop of the Grits is interrupted in places by narrow zones of Birkhill Shales, in some cases with Ordovician members of the Moffat Series, universally interpreted until recently as anticlinal inliers. Hawick Rocks lie to the south-east and are well exposed on the coast between the Mull of Galloway and Kirkcudbright.

The Queensberry Grits in the Glenluce area, studied recently by Gordon, may be represented by the Garheugh Formation, a group of greywackes with current-bedded siltstones and shales. No fossils have been found in these

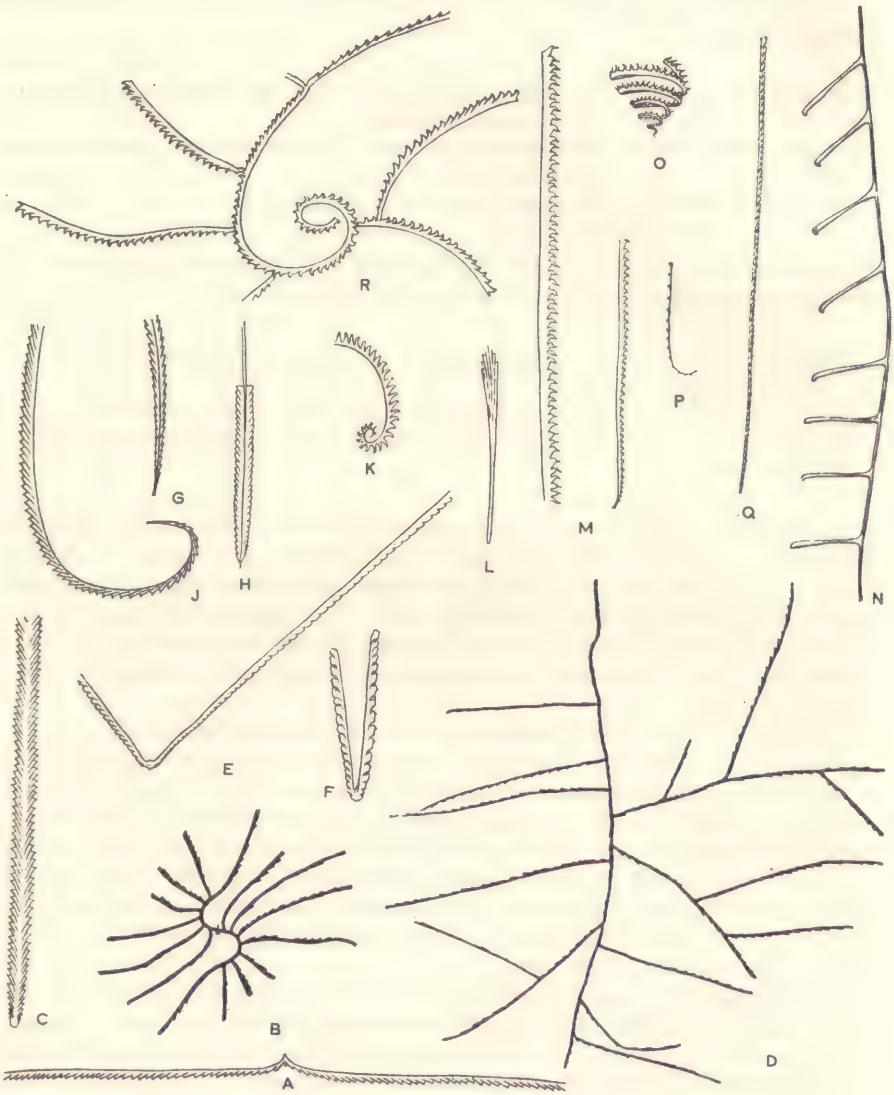


FIG. 8. *Ordovician and Silurian Graptolites*

(All drawings natural size after Elles and Wood.)

Ordovician, Arenig Series, **A**, *Didymograptus extensus* (Hall). Glenkiln Shales, **B**, *Nemagraptus gracilis* (Hall). Hartfell Shales, **C**, *Orthograptus truncatus* (Lapworth), **D**, *Pleurograptus linearis* (Carruthers), **E**, *Dicellograptus complanatus* Lapworth, **F**, *Dicellograptus anceps* (Nicholson). Silurian, Lower Birkhill Shales, **G**, *Akidograptus acuminatus* (Nicholson), **H**, *Diplograptus modestus* Lapworth, **J**, *Monograptus cyphus* Lapworth, **K**, *M. fimbriatus* (Nicholson). Upper Birkhill Shales, **L**, *Cephalograptus cometa* (Geinitz), **M**, *M. sedgwickii* (Portlock), **N**, *Rastrites maximus* Carruthers, **O**, *M. turriculatus* (Barrande), **P**, *M. crispus* Lapworth, **Q**, *M. griestoniensis* (Nicol). Wenlock Series, **R**, *Cyrtograptus murchisoni* Carruthers.

rocks, which include red and green shales and a boulder conglomerate, as seen elsewhere in the Queensberry Grits. The outcrop of the formation includes an inlier of graptolitic Birkhill Shales and is bounded to the north-west and south-east by, respectively, a group of greywackes of Birkhill Shales age, the Kilfillan Formation, and the Hawick Rocks, which crop out between Kirkmaiden and Burrow Head. The nature of the inter-formational boundaries is not clear.

These Hawick Rocks have been divided by Rust into the older Carghidown beds, characterized by the occurrence of primary red beds, and the younger Kirkmaiden beds, which have yielded graptolites characteristic of the zones of *M. griestoniensis* and *M. crenulatus*, the highest of the Llandovery Series. From the Carghidown beds through the Kirkmaiden beds into the older Garheugh Formation the direction of upward sequence is universally north-westward, and it is therefore concluded that the boundary between the last two groups is a strike-fault with a large down-throw towards the south-east.

Between Wigtown Bay and Kirkcudbright the Hawick Rocks consist of thin greywackes with siltstones and unfossiliferous shales, in some cases red in colour. Craig and Walton demonstrated that here too the direction of upward succession is nearly always north-westwards. They recognized a transition in this direction from the Wenlockian Riccarton Beds, with graptolitic shales, to the Hawick Rocks, and concluded that the latter formation is the younger, and of Wenlock or Ludlow age. They suggested also that the Queensberry Grits too might be partly Wenlockian. Rust contends that the Riccarton–Hawick boundary is a fault, and that the apparent interbedding of graptolitic (Riccarton) shales with red (Hawick) shales is the result of fault-slicing. The northern boundary of the Hawick Rocks is a strike-fault, as in the Kirkmaiden district. Structurally the Hawick Rocks may be divided into three broad zones. The central zone consists of closely folded beds in which the *faltenspiegel* (p. 9) is almost horizontal, whereas to north and south the steeply dipping strata are little folded, and young consistently towards the north-west. Subsequent research by Craig and Walton has reinforced their belief in the unbroken upward passage from the Riccarton Beds to the Hawick Rocks. It has also shown that the Raeberry Castle Beds, formerly considered to be Wenlockian, include graptolites of the Llandoverian zones of *Monograptus gregarius*, *M. sedgwickii*, and *M. crispus*, and lie in normal succession below the Riccarton Beds. They are typically developed, to a thickness of at least 400 m, on the coast eastwards from Kirkcudbright Bay, and consist of thin greywackes, olive-green shales with limestone nodules, and occasional bands of fossiliferous grit and conglomerate, the 'Balmae Grits'. The shales have yielded gastropods, bivalves, and cephalopods such as '*Orthoceras*' *etheridgei*. The fauna of the 'Balmae Grits' includes corals, crinoids, bryozoans, brachiopods, molluscs, and trilobites. A fossiliferous grit with a similar fauna occurs in the Wenlockian Zone of *Cyrtograptus linnarssoni* at Wrae Hill, north of Langholm (p. 44).

To the east and north-east of the Moffat area the rocks of the Gala Group are less massive and coarse-grained, and are often fossiliferous. Graptolitic shales occur at Deloraine in the upper Ettrick, some 16 km south-west of Selkirk, and in the Tima Water and Rankle Burn, large right-bank tributaries. The old Grieston slate quarry, west of Howford, is one of several graptolite localities near Innerleithen, and was one of the first to be recorded in the

south of Scotland. Blue and grey shales with limestones and calcareous ribs yield *Monograptus griestoniensis*, *M. priodon*, and other graptolites. The Queensberry (Buckholm) Grits are well exposed on Buckholm Hill, at Clovenfords, and in the Caddon Water, to the north and west of Galashiels. The shales locally yield graptolites of the zones of *M. turriculatus* and *M. crispus*, and the bedding-planes are locally covered with trace-fossils such as *Crossopodia* and *Nereites*. These last are particularly common in old quarries at Thornylee, west of Clovenfords, and Greenhill, south of Selkirk. Graptolites have been recorded from many sections near Lauder, but in the Easter Burn, some 8 km to the north-east, a fine-grained conglomerate has yielded poorly preserved corals, crinoid stems, and brachiopods, which have suggested a correlation with the Blackwood Beds of the Girvan area (p. 48).

Between Selkirk and Hawick lies the type-area of the Hawick Rocks. They consist of shales and thin greywackes, and, apart from trace-fossils, and fragments of the crustacean *Ceratiocaris* found near Hawick, they have yielded no fossils. In the Jed Water just south of Jedburgh vertical Hawick Rocks are overlain by horizontal beds of the Old Red Sandstone in a striking unconformity first recorded by Hutton.

Warren has recently postulated that the Hawick Rocks of Hawick belong to the Wenlock Series (see below). Their boundary with the Wenlockian Stobs Castle Beds appears to exhibit a transitional lithology which includes the red shales of the Hawick Rocks and the graptolitic shales of the Stobs Castle Beds. Warren sees no evidence at the boundary of the strike-fault, with a throw of at least 3500 m, which would have to be present if the Hawick Rocks were the older formation, but Rust dismisses this difficulty and interprets the evidence here in the same way as in the Kirkcudbright area (p. 41).

In Berwickshire there are two general areas of Llandovery rocks separated from each other and from the main outcrop by strips of Upper Old Red Sandstone rocks. On the coast for more than 9 km west of St. Abb's Head the Queensberry Grits are almost continuously exposed (Plate IIB). They consist of greywackes, siltstones and shales, which are locally graptolitic, many of the bands of greywacke attaining a thickness of 6 m or more. The spectacular unconformity of the Upper Old Red Sandstone on the Llandovery at Siccar Point (Plate I) near the western end of the outcrop, is of considerable historical importance because of its inspiring influence on the developing ideas of Hutton as a result of his visit to the locality in 1788. The impressive folding of the Queensberry Grits in this area prompted Hall to conduct the earliest laboratory studies of tectonics, by which he showed how rocks might be folded under horizontal compression. Many of the folds are markedly asymmetrical, and strike-faults, usually of small throw, are commonly developed in the axial regions. From west to east the direction of dip of the axial planes changes from north-north-westward to south-south-eastward, the broad inverted-fan structure being similar to, and perhaps corresponding with, Lapworth's 'Hawick Exocline' or synclinorium (Fig. 1). However, if the incalculable effects of strike-faults are discounted, the beds which are exposed in the middle of the structure appear to be older than those on the flanks, and not younger as the name would suggest. In addition to minor intrusions of basic composition the rocks east of Fast Castle are in places cut by volcanic breccia, made up largely of fragments of greywacke and shale.

An isolated area of 'Silurian' rocks north of Eyemouth includes two formations, described and named by Shiells and Dearman. The same authors have recently suggested on structural grounds that the more northerly formation, the intensely folded Coldingham Beds, may be of Dalradian age. The Linkim Beds, lying to the south, are tectonically less complex, but the generally broad folds face downwards. The general structure of the two groups is interpreted as a pre-Devonian recumbent anticline, facing south-eastwards, with a horizontal axial plane. The outcrop of the Linkim Beds lies in the lower inverted limb and that of the Coldingham Beds in the upper uninverted limb, the boundary between the two formations being a reverse-fault with south-eastward hade. The first folding of the Coldingham Beds is not developed in the Linkim Beds and is thus inferred to be of pre-Gala Group age. The Linkim Beds are known to be of Silurian age by the recent discovery in them of monograptid material, during the resurvey of the area by the Geological Survey.

The Silurian rocks extending southwards from Eyemouth have many of the characteristics of the Hawick Rocks, including a marked absence of fossils. Their structure is locally complex and sharp flexures of fold axes have been described by Dearman and his collaborators.

Wenlock Rocks: Southern Uplands

The most westerly occurrence of Wenlock rocks is on Burrow Head in Wigtownshire, where a small area of Riccarton Beds (p. 41) is shown by Rust to be faulted against Hawick Rocks to the north, with some tectonic interjacency of the two formations. The graptolite fauna is that of the basal Wenlock Zone of *Cyrtograptus murchisoni* and includes excellent specimens of the zone-species. The formation is similar in fauna to the Stobs Castle Beds (p. 44), but its lithology of greywackes and shales lacks the red beds of that group.

On Meikle Ross, the headland east of Wigtown Bay, the Riccarton Beds are estimated by Craig and Walton to be at least 550 m thick. They consist of grey greywackes, about 0·6 m in average thickness, flaggy siltstones, shales, and slates, with thin bands of bluish grey graptolitic shales. Recent study of the graptolites has demonstrated the presence of the zones of *Cyrtograptus murchisoni*, *Monograptus riccartonensis*, and *C. ellesi*. Sedimentary structures occur on many bedding-planes and indicate a general flow of turbidity currents from the north-east. The adjacent Raeberry Castle Beds, deposited by currents from the south-west, and at times from the north-west, are described on p. 41.

The Riccarton Beds appear to be present in a narrow strip of altered Wenlock rocks south of the Criffell Granite. North-east of the River Nith they include the characteristic graptolites *C. murchisoni* and *Monograptus riccartonensis*, but the Raeberry Castle Beds are not recorded until the area of Langholm and Riccarton is reached.

South of Hawick, and in the Riccarton inlier to the south-east, the term 'Riccarton Group' has been applied by Warren to all the Wenlock rocks, which span the full range of Wenlockian time. He has subdivided the Group thus:

Caddroun Burn Beds	1500 m	Upper	*Cyrtograptus lundgreni*
		Lower	*C. rigidus*
Penchrise Burn Beds	450 m		*Monograptus riccartonensis*
Shankend Beds	600 m		
Stobs Castle Beds	1350 m		*C. murchisoni*

The zones of *C. ellesi* and *C. linnarssoni* are thought to be present between those of *C. lundgreni* and *C. rigidus*, but the zone-fossils themselves are generally rare in northern England and southern Scotland. The Zone of *C. linnarssoni* is, however, recognized in the Langholm area, adjacent to the west. The graptolite fauna resembles in some respects that of Bohemia, for example in the occurrence of *C. insectus* and *C. centrifugus* in the Zone of *C. murchisoni*.

The Stobs Castle Beds, which occur only in the main outcrop, consist of thin fine-grained greywackes, siltstones, greyish green and red mudstones, graptolitic shales, and carbonaceous, non-graptolitic shales. The higher formations are distinguished from each other mainly on a palaeontological basis. The Shankend Beds include massive greywackes, often coarse-grained, but lack red mudstones. A 3-metre band of coarse-grained greywacke, the 'Berryfell Grit', is the basal member of the Penchrise Burn Beds. Above, the greywackes become in general progressively finer-grained. Graptolite shales become more common in the Upper Caddroun Burn Beds, in which olive-green mudstones are characteristic.

In the Hawick–Riccarton area as a whole the structural pattern conforms with the modern hypothesis for the Southern Uplands, namely a succession of open asymmetrical north-west-facing folds, often with much close folding on the gently dipping limbs, the rocks becoming generally younger to the north-west. Large strike-faults with downthrow to the south-east outweigh the effect of the folds, so that the units between them are successively older towards the north-west.

Warren's interpretation of the 'Riccarton Group' in the Hawick area is confirmed by the recent revision by the Geological Survey of the ground adjacent to the west, near Langholm. The zones of *Cyrtograptus murchisoni*, *Monograptus riccartonensis*, and *C. linnarssoni* are recognized, the older rocks lying to the north-west although this is also the general direction of upward succession in individual exposures. Major shatter-belts, trending north-north-eastwards, are seen in two cases to mark wrench-faults with a sinistral displacement of about 800 m. One large strike-fault, with a southward downthrow, lies in the crestal region of a major north-facing anticline. Unusual lithological features are the development of ironstone nodules in mudstone at two places, and of thin tuffs in three places, apparently in the Zone of *C. linnarssoni*.

North-east of the Riccarton inlier, between the Cheviot Hills and Jedburgh, there are several small inliers of Wenlock rocks within the Old Red Sandstone. The largest are in the valley of the Jed Water some 10 km above Jedburgh, in

the uplands of the Leithope Forest to the east, and around Oxnam, about 6 km east of Jedburgh. Small patches of Silurian rocks occur here and there in this general area, usually with graptolites of the Zone of *M. riccartonensis* and clearly overlain unconformably by the Old Red Sandstone.

Llandovery Rocks: Girvan Area

The facies change seen in the Central Belt as the Birkhill Shales are followed north-westwards from the 'Moffat Line' (p. 38) is continued into the Girvan district, where rocks of this age constitute the **Newlands Series**. The Series occurs in three separate areas, in the Craighead Inlier north-west of Dailly, at Woodland Bay, and in a narrow outcrop extending north-eastwards and south-westwards for some 5 km through Camregan Hill. The subdivision shown below was established by Lapworth, and the correlation with the succession at Llandovery by Freshney. The Zone of *M. convolutus* includes at the top a band with *Cephalograptus cometa*, the zone-fossil of Lapworth's Birkhill classification. Except for the *R. maximus* Shales all these beds have been recognized in the Craighead Inlier, but south of the Girvan Valley *Pentamerus* Grits are the lowest Silurian rocks exposed.

The Mulloch Hill Group is well seen in the Craighead Inlier. Lamont suggested that the High Mains sandstone, unconformable on Ordovician rocks, should be taken as the basal member of the Group. It has, however, yielded the brachiopod *Hirnantia* ['*Orthis*'] *sagittifera*, a form characteristic of the topmost part of the Ashgill Series. The overlying conglomerate is mainly composed of pebbles of Ordovician volcanic and associated plutonic rocks, chert, and quartzite, embedded in a sandy matrix of a dull purple colour. Fossils obtained from the conglomerate at Quarrel Hill are mainly forms of brachiopods not seen in lower beds, thus emphasizing, as in the

Stage	Graptolite Zone	Local Classification	
Upper Llandovery	*Rastrites maximus*	Upper Camregan Grits *Rastrites maximus* Shales Camregan Grit and Limestone *Rhynchonella* Grits	Camregan Group 60 m
	Monograptus sedgwickii	*Monograptus sedgwickii* Shales	
Middle Llandovery	*M. convolutus* *M. gregarius* *M. cyphus*	Saugh Hill Sandstones and Grits Glenshalloch Shales Newlands *Pentamerus* Grits	Saugh Hill Group 150 m
Lower Llandovery	*Orthograptus vesiculosus* *Akidograptus acuminatus*	Glenwells Shales Mulloch Hill Sandstone Mulloch Hill Conglomerate	Mulloch Hill Group 110 m

Moffat Series, the palaeontological break between the Ordovician and Silurian rocks. The Mulloch Hill Sandstone consists of green and yellow sandstones and mudstones which are calcareous and highly fossiliferous. Typical Lower Llandovery brachiopods are common, such as *Cryptothyrella angustifrons*, *Dalmanella biconvexa*, and *Leptostrophia mullochensis*. Other characteristic fossils are *Heliolites interstinctus*, *Pinacopora grayi*, *Clorinda undata*, '*Camarotoechia*' *llandoveriana*, *Leangella scissa*, *Schizophorella mullochensis*, *Stricklandia lens*, *Conularia sowerbyi* and species of *Calymene*, *Encrinurus*, and *Illaenus*. The green and blue concretionary mudstones of the Glenwells Shales include striped shales from which Lapworth recorded *Akidograptus acuminatus*, *Climacograptus normalis*, and *Monograptus atavus*. A thin green conglomerate marks the top of the Shales.

In the Craighead Inlier the *Pentamerus* Grits appear to have an unconformable and overstepping relationship to the underlying Glenwells Shales and Mulloch Hill Sandstone. They are fine-grained calcareous sandstones and grits, weathering yellow or brown, with an abundant fauna characterized by *Clorinda undata*, with *Encrinurus* and other trilobites. Other fossils from the Grits are *Halysites catenularia*, *Coolinia* [*Fardenia*] *applanata*, *Craniops implicata*, *Resserella sp.*, *Stricklandia lens*, *Cyrtolites*, *Platyceras*, *Orthoceras*, *Acidaspis*, *Calymene*, *Cheirurus*, *Illaenus*, *Lichas*, *Phacops*, and *Staurocephalus*. The overlying grey and black flaggy shales are named alternatively from Glenshalloch, in the Craighead Inlier, or from the graptolites *Diplograptus modestus* and *Monograptus gregarius* which are found in them. The fauna includes also *Climacograptus normalis*, *Glyptograptus tamariscus*, *Monograptus argutus*, *M. atavus*, *M. crenularis*, *M. fimbriatus*, *M. leptotheca*, *Petalograptus palmeus*, and *Rastrites peregrinus*. Some pebbly beds occur in the upper part of the formation. The succeeding thick pebbly sandstones, until recently regarded as being of Old Red Sandstone age, resemble the Saugh Hill Grits and have yielded unidentifiable brachiopods.

The succession is continued in the Craighead Inlier by greyish brown shales and mudstones, formerly mapped as Old Red Sandstone but now assigned by Freshney to the *M. sedgwickii* Shales. They contain *Monograptus variabilis*, *Petalograptus palmeus*, *and Trematis sp.*, and pass upwards into purple sandstones and conglomerates with a brachiopod-trilobite fauna which includes such forms as *Pentamerus oblongus*, *Pholidostrophia sefinensis*, and *Eocoelia sp.*, all indicative of the Upper Llandovery. These sandy beds appear to be correlative with part of the Camregan Group and are unconformably succeeded to the north by the Old Red Sandstone.

The Llandovery outcrop of Camregan Hill is fault-bounded to the south and along most of its northern edge, the beds in many places seeming to dip beneath the Ordovician. In Penwhapple Glen, east of Camregan Hill, the oldest Silurian rocks are green and grey calcareous flags and shales which have yielded specimens of *Clorinda* and are probably equivalent to part of the Woodland Limestone (see below). They are succeeded by the Glenshalloch Shales, black mudstones and shales with a rich graptolite fauna, including *Climacograptus hughesi*, *C. normalis*, *Dimorphograptus swanstoni*, *Glyptograptus tamariscus*, *Diplograptus modestus*, *Monograptus crenularis*, *M. gregarius*, *M. leptotheca*, and *Petalograptus palmeus*. The Shales are followed by the Saugh Hill Grits, which form a prominent feature at the type-locality, south-west of Camregan Hill, where they contain bands of conglomerate and

a breccia with angular fragments of grit and shale. The *M. sedgwickii* Shales are well exposed in Penwhapple Glen. They consist of greyish green and black mudstones and shales, with graptolites especially abundant in the upper beds. The assemblage includes *Monograptus convolutus*, *M. intermedius*, *M. nudus*, *M. sedgwickii*, and *Rastrites peregrinus*.

The basal beds of the Camregan Group succeed the *M. sedgwickii* Shales in Penwhapple Glen. The massive basal grits and flags, with rhynchonellid casts, are inverted and are succeeded to north-west by flags and limestones, and beyond by fossiliferous calcareous shales and mudstones. The fauna includes brachiopods and trilobites, such as *Cyrtia exporrecta*, *Dicoelosia biloba*, *Dolerorthis rustica*, *Eospirifer plicatellus*, *Pentamerus oblongus*, *Protomegastrophia walmstedti*, '*Rhynchospira*' *camreganensis*, *Acidaspis bispinosus*, *Calymene blumenbachi*, *Encrinurus mullochensis*, *Eophacops elegans*, *Illaenus sp*, *Scutellum andersoni* and *Youngia trispinosa*. These beds are overlain by purple and green mudstones with a band of dark shale yielding *Monograptus nudus*, *M. runcinatus*, *M. turriculatus*, *Petalograptus palmeus*, and *Rastrites maximus*, characteristic of the highest Birkhill Zone of *R. maximus*. The massive unfossiliferous Upper Camregan Grits which succeed these shales may be more correctly assigned to the base of the Dailly Series. Fossiliferous grits and shelly mudstones of the Camregan Group, and the *R. maximus* Shales at the top, are exposed in Lauchlan Burn, about 2 km to the east.

The Newlands Series is also exposed in the area of Woodland Bay. At the northern end the basal conglomerate of the Saugh Hill Group forms the prominent Horse Rock. It is 15 m thick and rests unconformably on Ordovician rocks. Beds with pebbles of chert, greywacke, and gneissose rocks, are interbedded with thick bands of green grit. They are approximately coeval with the oldest Silurian rocks of Penwhapple Glen, but in appearance and pebble-content have been closely compared with the Ordovician conglomerates of the Corsewall Group in Galloway. Nearby on the islet of Craigskelly, which has locally given its name to the bed, the grits contain *Atrypa reticularis*, *Eocoelia hemisphaerica*, and *Strophomena*. The impure flaggy limestone above is known as the Woodland Limestone and contains *Alveolites labechei*, *Favosites gothlandicus*, and such brachiopods as *Stricklandia lens*. At Woodland Point, at the southern end of the bay, the limestone is about 9 m thick. The long list of fossils collected from it includes sponges, corals, brachiopods, gastropods, cephalopods, and trilobites. Here and at Craigskelly it is succeeded by the Glenshalloch Shales which have yielded, from thin dark beds, *Climacograptus normalis*, *Dictyonema sp.*, *Diplograptus modestus*, *Monograptus atavus*, and *M. cyphus*. The highest beds are conglomerates and sandstones, which at Woodland Point are correlated with the Saugh Hill Sandstones and Grits and are divided into a basal quartz-conglomerate and the Scart grits and conglomeratic sandstones above.

The Gala Group is represented in the Girvan area by the lower part of the **Dailly Series.** The rocks are divided as follows:

Drumyork Group and Bargany Group 330 m	Green flagstones and shales, unfossiliferous Yellow, blue, and grey flagstones with shales (Blackwood Beds) Pale blue thick-bedded flagstones and shales (Glenfoot Beds)

Penkill Group 300 m	*Crytograptus grayi* mudstones and shales *Protovirgularia* grits Penkill flags and shales Purple shales and mudstones with *Crossopodia*, etc.

They occupy a narrow area between Penwhapple Glen and Knockgardner, some 8 km east-north-east of Dailly. North-eastwards from Hadyard Hill, south of Dailly, the outcrop is for much of its length a very narrow strip upfaulted between Old Red Sandstone and Carboniferous rocks. Normal stratigraphical junctions with the Wenlock Series and with the unconformable Old Red Sandstone occur beyond, respectively, the north-eastern and south-western ends of this strip.

The *Crossopodia* Shales resemble in lithology and fauna the 'slates' of Thornylee Quarry, near Clovenfords (p. 42), and are covered with annelid tracks, such as *Crossopodia scotica*, *Myrianites tenuis*, *Nereites sedgwicki*, and *N. cambrensis*. The dark shales yield many graptolites, including *Monograptus becki*, *M. exiguus*, *M. galaensis*, *Rastrites equidistans*, and *Retiolites obesus*, indicative of the basal Gala Zone of *M. turriculatus*. In Penwhapple Glen the grits and flaggy greywackes which succeed the *Crossopodia* Shales are perhaps equivalent to part of the Queensberry Grits, and are equally poor in fossils. In the succeeding *Cyrtograptus* Mudstones there is an interesting mixture of graptolitic and shelly faunas. Well displayed in the Glen the rocks include the following fossils: *Cyrtograptus grayi*, *M. galaensis*, *M. marri*, *M. nudus*, *Rastrites equidistans*, *Atrypa reticularis*, *Cyrtia exporrecta*, *Dolerorthis rustica*, *Glassia obovata*, *Leptaena rhomboidalis*, *Eoplectodonta penkillensis*, *Triplesia insularis*, *Lunulicardium elegans*, and *Dawsonoceras annulatum*.

The Glenfoot Beds are well exposed near the foot of Penwhapple Glen and in another burn some 2·6 km to the north-east. In the latter locality they are succeeded to the north-west by the Blackwood Beds, which include thin beds containing *Monograptus acus* and *M. priodon*. In this burn also, about 100 m south of the fault which truncates the Lower Palaeozoic succession, shales with limestone ribs have yielded fossil plants and a fauna which includes *Heliolites interstinctus*, *Palaeocyclus sp.*, '*Orthis*' *polygramma*, *Pentamerus oblongus*, *Poleumita discors* and *Discinocaris gigas*.

The Drumyork Group forms a narrow outcrop, steeply inverted towards the south-east, near Drumyork, about 6 km east-north-east of Dailly. From its lithology and unfossiliferous character, and its position immediately below the Wenlock rocks to the north-west, the Group was tentatively

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PLATE IV

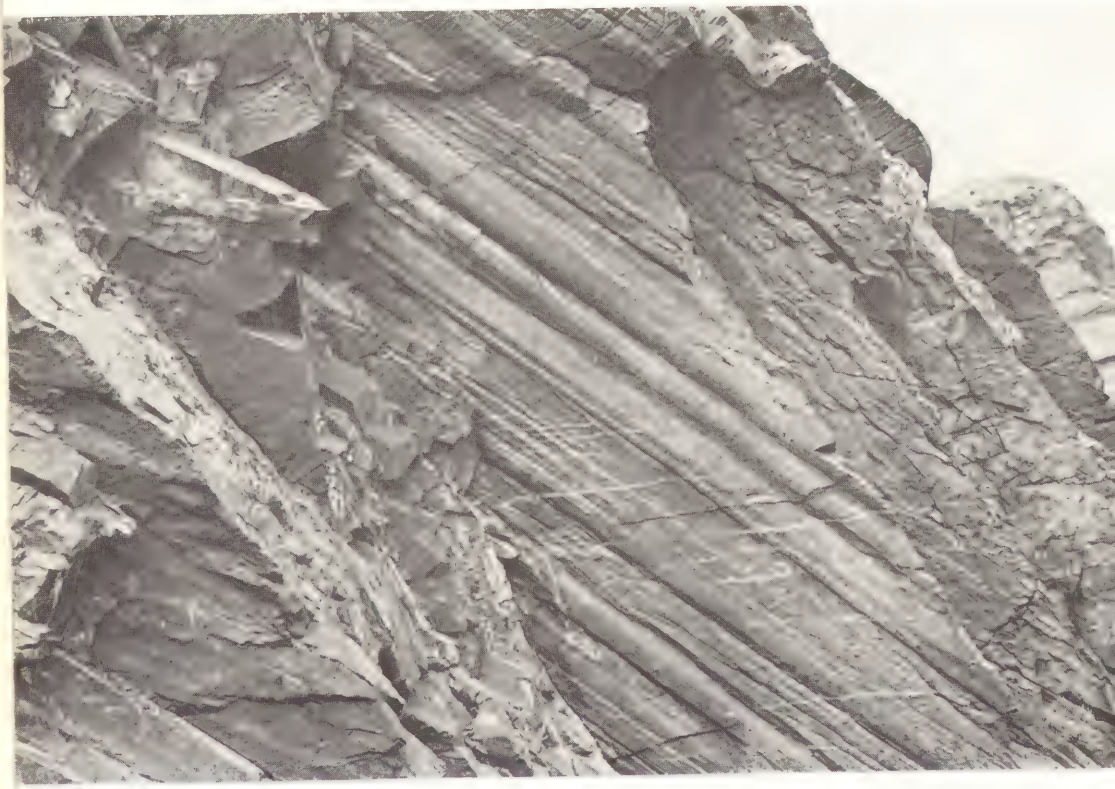
A. Bedding and axial-plane cleavage in Silurian rocks, about 8 km north of Langholm, Dumfriesshire. Greywacke, siltstone, and mudstone, with a marked cleavage in the mudstone beds. The gentler dip of the cleavage indicates that the beds are inverted, the original upper surface being to the right. (Geol. Surv. Photo. No. D617).

B. Ripple-marked Silurian greywacke, Berwickshire. Transverse current ripple-marks on upper surfaces of thinly bedded greywackes and siltstones. Haud Yauds, about 7 km north-west of Coldingham. (Geol. Surv. Photo. No. D1226).

A

B

PLATE V



A

B

correlated by Peach and Horne with the Hawick Rocks. Lapworth however had grouped them with the Straiton beds and Walton has pointed out that they may be of Wenlock age, together with the Bargany Group and at least part of the Penkill Group.

Wenlock Rocks: Girvan Area

Rocks of the **Straiton Group,** the upper part of the Dailly Series, form a narrow outcrop, some 8 km long, which extends south-westward from Straiton to beyond Drumyork. Except in the Drumyork area, where they rest conformably on the flags of the Drumyork Group, the south-eastern boundary of these Wenlock rocks is a fault. To the north-west they are succeeded unconformably by the Upper Old Red Sandstone, and immediately north-east of Straiton they are faulted against Lower Carboniferous rocks. The lower beds, the Blair Shales, contain an abundance of graptolites in thin layers of dark shale, and from a quarry near Blair, just west of Drumyork, the following forms have been recorded: *Cyrtograptus sp.*, *Monograptus flemingi*, *M. priodon*, *M. riccartonensis*, *M. vomerinus*, and *Retiolites geinitzianus*. In associated strata there is a varied fauna including corals, brachiopods, cephalopods, and arthropods. The higher beds, the Straiton Grits and Conglomerates, include some fossiliferous bands of grit in the ground east of Knockgardner. The fauna includes *Atrypa reticularis*, *Eoplectodonta transversalis*, *Resserella* cf. *elegantula*, *Acaste downingiae*, *Calymene blumenbachi*, *Encrinurus punctatus*, and *Warburgella stokesi*.

PLATE V

A. Linear groove-casts in Silurian greywacke, Berwickshire. The casts, on the under surface of a bed of greywacke, are the infilling of grooves eroded in the sea-floor by the passage of solid objects, such as rock fragments, at the base of the material suspended in a turbidity current. Shore 5·5 km north-west of St. Abbs. (Geol. Surv. Photo. No. D1227).

B. Longitudinal ripple-casts on the under surface of a bed of Silurian greywacke. The dendritic pattern shows mutual interference between casts. Windy Cleuch, about 3 km west-north-west of Riccarton Junction, Roxburghshire. (Geol. Surv. Photo. No. D658).

5. OLD RED SANDSTONE

Prior to the deposition of the Old Red Sandstone the older rocks underwent severe earth-movements and were subjected to great erosion. Part of the area became a basin of deposition, the floor of which was occupied by one or more lakes. The deposits fall into two distinct subdivisions—the Lower Old Red Sandstone and the Upper Old Red Sandstone. The earliest sediments were laid down on the upturned edges of the older rocks, and consist of sandstones and conglomerates, the latter being deposited as torrential gravels. Great thicknesses of lava were poured out of volcanoes situated along the flanks of the high ground bordering the depressed area, and some of the lavas appear to have flowed into the lakes where they were later covered by sediments which were partly lacustrine and partly fluviatile in origin.

Further upheaval and very extensive denudation of the area is indicated by the marked unconformity at the base of the Upper Old Red Sandstone, and during the subsidence which followed sediments consisting mainly of conglomerates, sandstones and marls were spread over the Lower Palaeozoic rocks far beyond the boundary of the earlier basin. Cornstones, nodular or lenticular masses of fine-grained limestone and sandy limestone, are numerous in the upper part of the succession, and, as pointed out by Burgess, may possibly represent soil replacement deposits formed in semi-arid conditions.

The problems concerning the junction between the Upper Old Red Sandstone and the Carboniferous are discussed on p. 63. It is very probable that in this region the Upper Old Red Sandstone facies persisted into Carboniferous times, and that at least some of the strata here described as Upper Old Red Sandstone are in fact of Carboniferous age.

Lower Old Red Sandstone

As a result of pre-Upper Old Red Sandstone denudation, the Lower Old Red Sandstone occupies relatively small areas in the Girvan district and in the counties of Roxburgh and Berwick. In the latter area the rocks are exposed near Eyemouth, Reston, and St. Abbs. They include red feldspathic sandstones and conglomerates, with a few thin cornstones and partings of red marl, which were laid down in a freshwater lake, and associated beds of coarse tuff and flows of andesitic lava (Plate VIA). The volcanic rocks are estimated to be at least 600 m thick. In the neighbourhood of Eyemouth and St. Abbs several vents filled with agglomerate largely composed of andesitic fragments are well exposed on the shore. The age of the sediments and lavas is determined by the occurrence of *Pterygotus*, and also by the fact that the beds are unconformably overlain by the Upper Old Red Sandstone.

In Roxburghshire the Lower Old Red Sandstone is mainly represented by a great thickness of lavas which form part of the Cheviot Volcanic Series. The lava-flows are predominantly andesitic and include basaltic andesites and

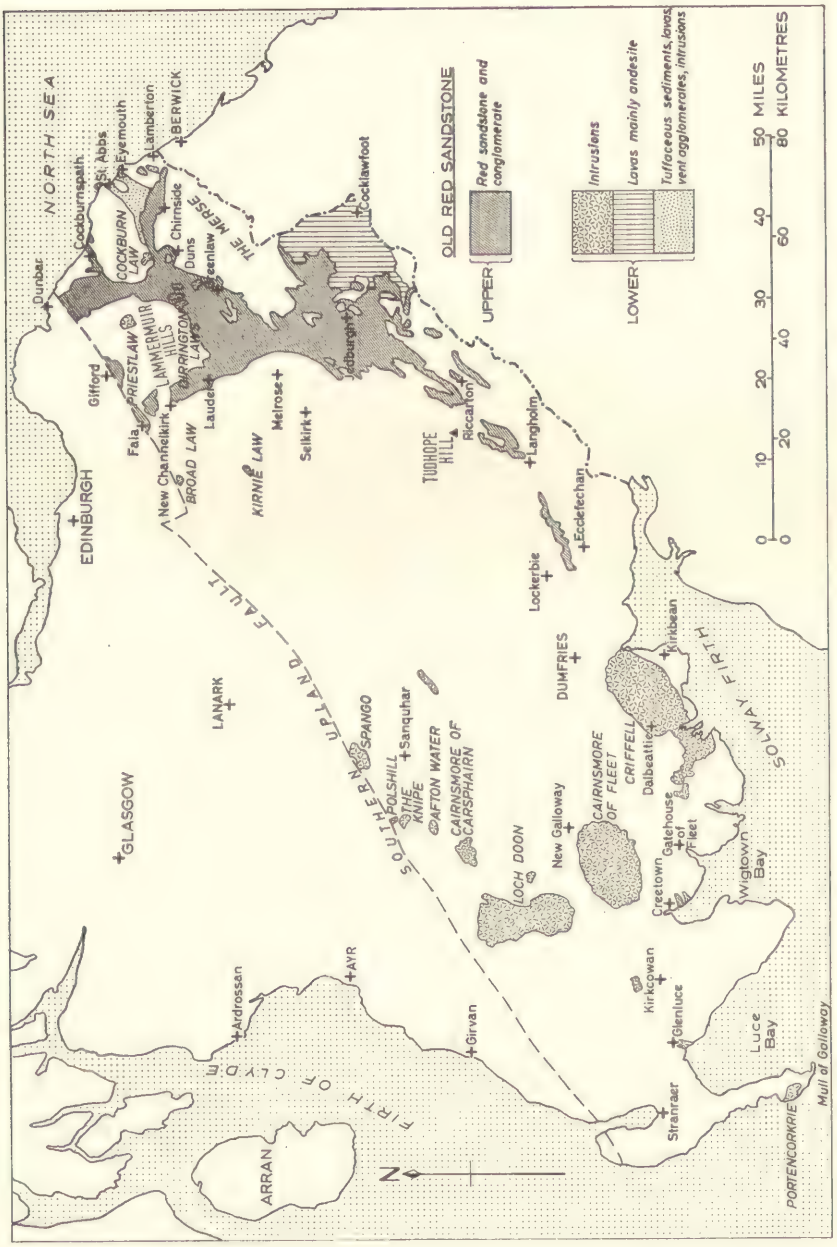


FIG. 9. *Outcrops of the Old Red Sandstone in the South of Scotland*

felsic glassy pyroxene-andesites; rare mica-felsites have also been recorded. In places the rocks are vesicular and agates have been found in the vesicles. While the flows are locally separated by beds of tuff, there are few intercalations of sediment. Isolated patches of coarse breccia probably indicate the sites of volcanic vents; such a patch has been mapped near Cocklawfoot at the head of Bowmont Water.

In addition to the lavas, numerous intrusions of Lower Old Red Sandstone age occur in the region, and the most striking feature of this igneous activity is the prevalence of a granodioritic or tonalitic magma over a wide area. In the eastern part of the Uplands the intrusions occupy small areas at Priestlaw in the Lammermuirs, and at Cockburn Law and Stoneshiel Hill, near Duns. Smaller masses also occur on Broad Law in the Moorfoot Hills and Kirnie Law, near Innerleithen. Near Lamberton Beach, 2·5 km south-south-east of Burnmouth, there is a small knob of granodiorite or quartz-diorite, but the commonest type is basic hornblende-biotite-granodiorite. At one time the intrusive masses of Dirrington Laws, Blacksmill Hill and Kyles Hill near Duns were regarded as being of Lower Old Red Sandstone age, but evidence was brought forward by Irving that they may be Carboniferous. The field-evidence, although not conclusive, is considered by A. G. MacGregor to favour the older view (see also p. 89).

The more important intrusions, however, are the Loch Doon, Cairnsmore of Fleet, and Criffell granitic masses in Galloway. The first is intruded into Ordovician rocks, along with smaller intrusions such as Cairnsmore of Carsphairn, The Knipe, Afton Water and the granodiorite of Spango Water (Fig. 9). The rocks surrounding the Cairnsmore of Fleet mass are mainly Silurian, but also include some of Ordovician age, while the Criffell complex is intrusive in Silurian strata.

The Loch Doon mass occupies an area extending from Loch Doon to Loch Dee, a distance of over 18 km (Fig. 10). It has a maximum width of 10·5 km and is surrounded by a girdle of altered sediments which form the Kells Range to the east and Merrick to the west. Gardiner and Reynolds subdivided the plutonic rocks into three main types, a basic rock (norite), an intermediate rock (tonalite) and an acid rock (granite), while more recent work by Higazy indicates that the chief plutonic rocks of the complex are norite, diorite, granodiorite and adamellite. The description given below is based on the work of Gardiner and Reynolds. The granite forms a central ridge of hills, the highest of which is Mullwharchar. The rock is a biotite-granite, nearly white in colour, and consists of quartz, biotite and orthoclase with microcline and oligoclase. Occasional crystals of orthoclase and microcline occur as phenocrysts, and muscovite and hornblende are sometimes present. The tonalite and other closely allied rocks occupy the country on either side of the central ridge, and are generally grey in colour. The commonest variety consists of oligoclase, biotite and quartz, with or without subordinate orthoclase and hornblende. In many places the tonalite contains xenoliths of highly altered sediments, and over much of the contact between the tonalitic mass and the surrounding sediments a distinctive type of rock is formed, dark in colour, fine-grained and highly biotitic.

There are two principal masses of norite in the Loch Doon complex, at the southern and north-western ends, and along the greater part of their outer boundaries they are in contact with Ordovician sediments. The norite is a dark-coloured medium- to coarse-grained rock composed of plagioclase, rhombic pyroxene (hypersthene and enstatite) and augite, and in the more granitoid types quartz and orthoclase occur as interstitial matter. The marginal mingling of norite and tonalite magma has produced rocks of hybrid character.

The granitic mass of Cairnsmore of Fleet occupies an oval-shaped area

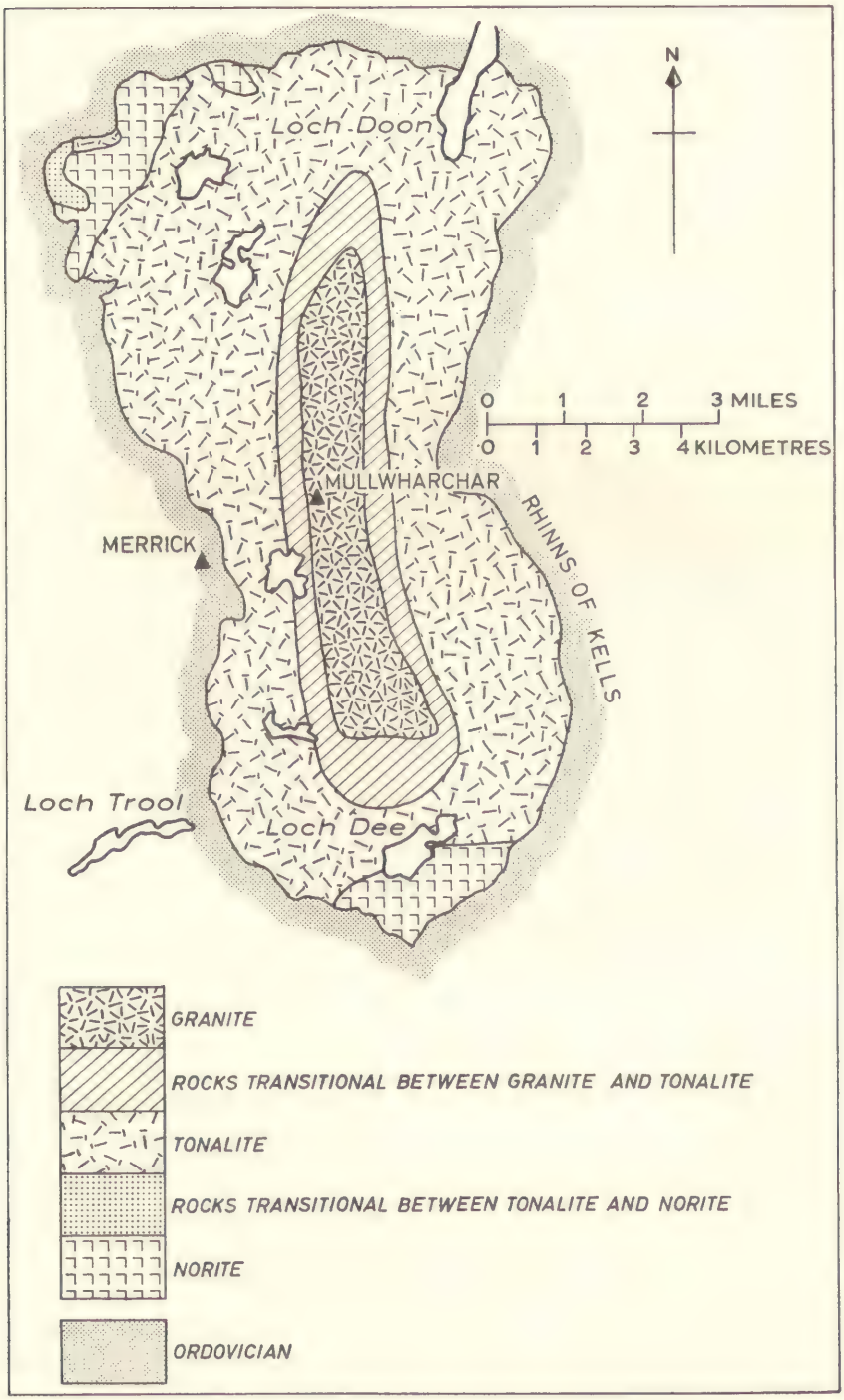


FIG. 10. *The Loch Doon Granite and associated rocks*
(Based on Gardiner and Reynolds 1932, pl. IV.)

17 km long and 11 km wide lying between the Loch Doon mass and the Criffell complex. The longer axis of the pluton, trending north-east, is parallel to the regional strike of the country rocks. The outcrop of the mass is described by Gardiner and Reynolds as being composed of two related rock-types, an almost continuous marginal area of biotite-granite and a central muscovite-biotite-granite (Fig. 11); both are more acid in composition than the rocks of the two large adjacent complexes. The muscovite-biotite-granite forms the greater part of the outcrop, the principal constituents being muscovite, biotite, quartz, and microcline with oligoclase and orthoclase;

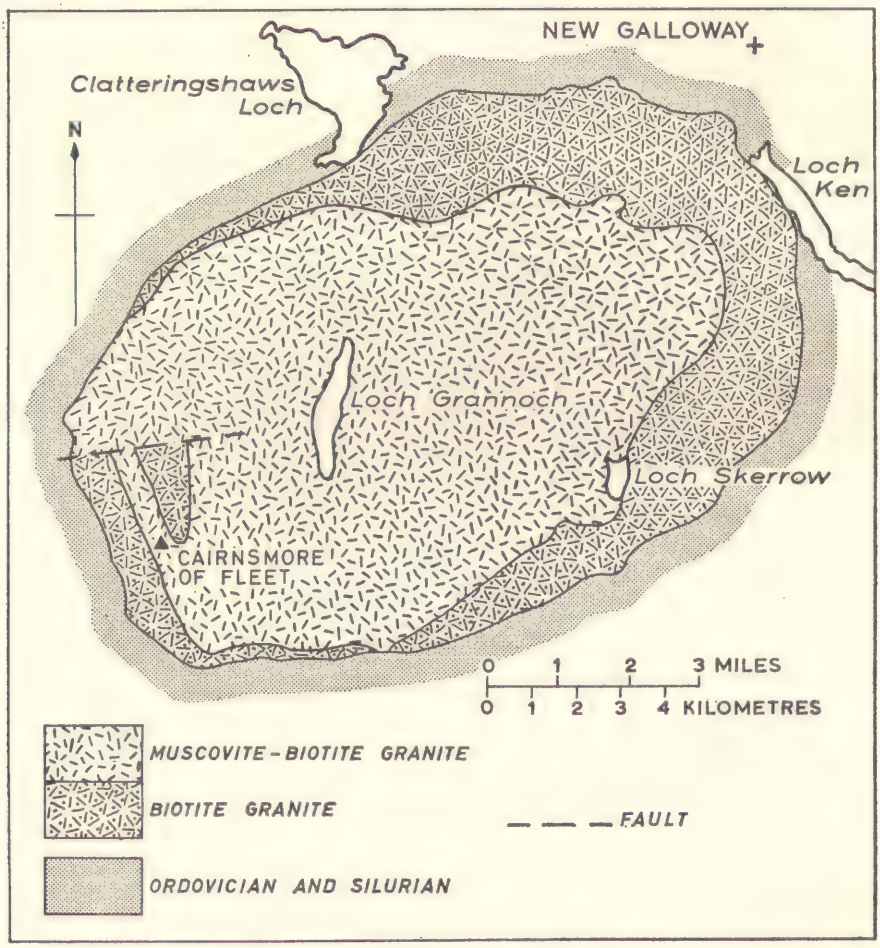


FIG. 11. *The Cairnsmore of Fleet Granite*
(Based on Gardiner and Reynolds 1937, fig. 1.)

hornblende has been noted only in one or two cases. The accessory minerals are apatite, zircon and iron-ores; the occurrence of monazite has also been recorded. Apart from the absence of muscovite, the composition of the outer granite is almost identical with that of the inner. The width of the outcrop of the outer granite is variable and reaches a maximum of about 3 km in the

north-eastern part. A distinctive foliation has been observed in the outer granite near Clatteringshaws Loch on the north-western margin of the mass.

The Criffell igneous complex forms an elevated tract of land, extending from the River Nith to Bengairn, a distance of 27 km (Fig. 12) (Plate VIB). East of the Urr Water the average breadth is 11 km. The longer axis of the mass has a north-easterly trend, coinciding with the regional strike of the Silurian rocks. The emplacement of the plutonic rocks has resulted in a pronounced deflection of the strike of the adjacent country rocks at the ends of the complex. The mass, described by Malcolm MacGregor and Phillips, includes three granodiorites with associated quartz-diorite rocks. The outcrop of the main granodiorite, which forms the greater part of the complex, extends from the north-eastern extremity of the mass to Torr Point in Auchencairn Bay, and is composed of a medium-grained rock which becomes porphyritic towards the centre of the outcrop. The medium-grained variety contains hornblende, plagioclase ranging from oligoclase to andesine, microperthite and quartz; sphene is prominent among the accessory minerals. Basic segregations are locally abundant along the margin of the intrusion. In the porphyritic granodiorite microperthite forms phenocrysts, hornblende is usually lacking, and the plagioclase is oligoclase. Two smaller areas of granodiorite are found at the south-west of the complex; both are finer-grained and more acid in composition than the rocks of the main mass. The most acid and most finely grained variety crops out in an ill-defined area on the west side of Auchencairn Bay; it contains more quartz and potash-feldspar and less plagioclase than the main granodiorite, and is flanked to the north, west and south by a granodiorite intermediate in composition and grain-size between the other two. On the north and west margins of the intermediate granodiorite lies the Bengairn quartz-diorite, typically grey in colour and composed essentially of quartz, potash feldspar, plagioclase, biotite and hornblende, with sphene, apatite and pyroxene as accessory minerals. Along the south-eastern margin of the main granodiorite, from Bainloch Hill to the eastern slopes of Criffell, and again along the northern margin, the rock has a marked foliated character, a secondary structure which may have been developed by dynamic action connected with earth-movements. A gravity survey by Bott and Masson-Smith suggests that the complex has a batholithic shape, probably reaching a depth of over 11 km. The contacts appear to slope outwards with depth at moderately steep angles.

Several smaller intrusions of similar composition occur outside the area occupied by the large masses just described. The outcrop of the Cairnsmore of Carsphairn igneous complex is roughly triangular, being about 6 km from west to east and about 4 km from north to south. A central area of granite is surrounded by a granite-tonalite hybrid, which is in turn encircled by a tonalite. On its northern margin the latter is in contact with the country rocks. The southern and eastern parts of the complex are composed of a group of basic hybrid rocks. There are no chilled margins between the four principal rock types in the complex, the contacts being transitional. The rocks of the two relatively small intrusions in the upper reaches of Afton Water, about 7 km north-east of the Cairnsmore of Carsphairn mass, include granodiorite and microdiorite.

The composition of the intrusion at The Knipe was shown by Walker to be almost identical with that at Polshill just to the north, where the centre of the

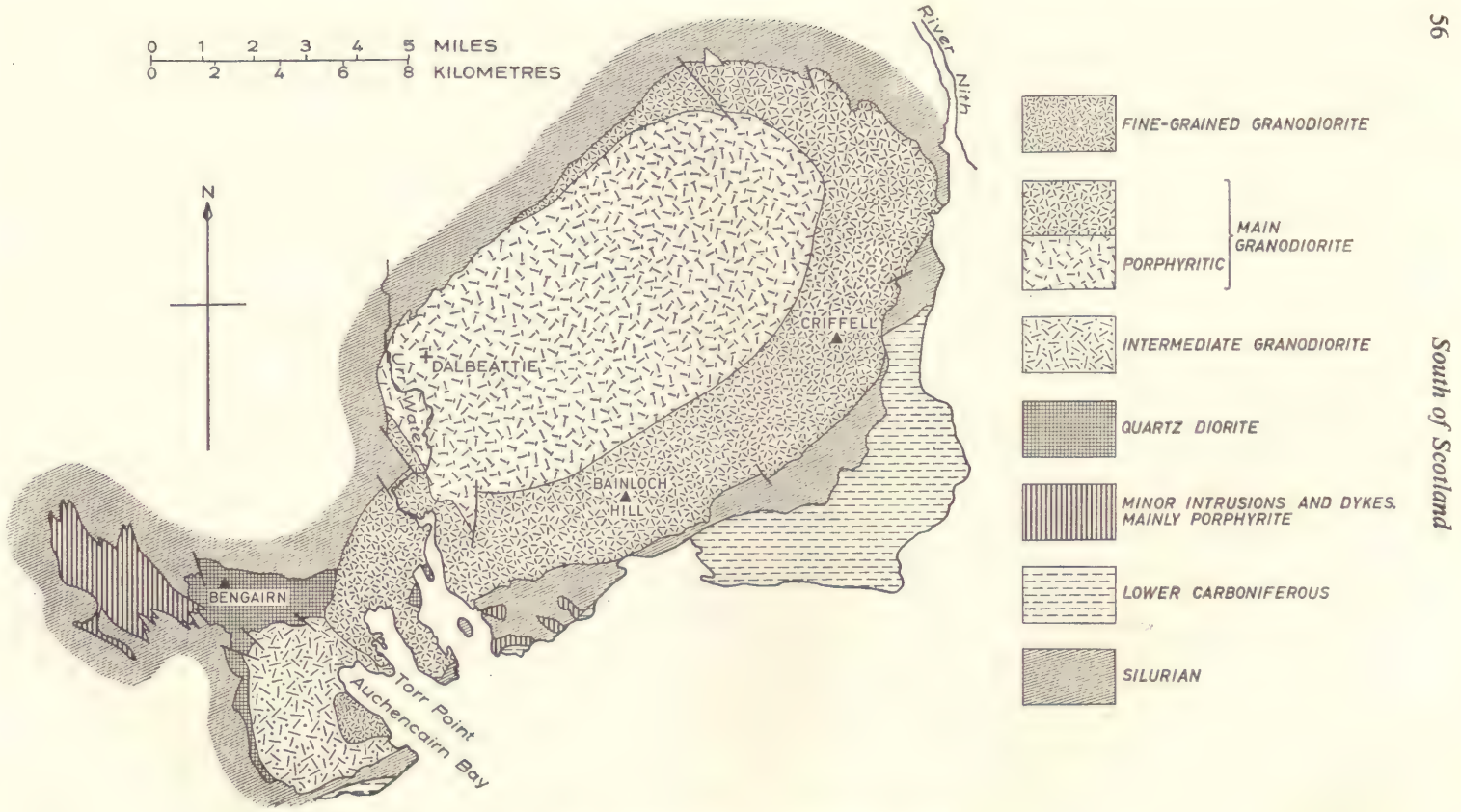


FIG. 12. *The Criffell Granite and associated rocks*
(Based on Phillips 1956a, pl. VII.)

mass is a basic hornblende-biotite-granodiorite or quartz-diorite which passes outwards into pyroxene-bearing modifications.

The Spango intrusion is a biotite-hornblende-granodiorite, containing numerous inclusions of greyish dioritic rocks which probably represent fragments of a relatively basic earlier intrusion caught up in the granodiorite.

The Portencorkrie complex, about 7 km north-west of the Mull of Galloway, is composed of an outer zone of pyroxene-mica-diorite and hornblende-mica-diorite, intruded by an inner mass of adamellite. The Glenluce intrusion and the mass north of Kirkcowan (Fig. 9) include quartz-diorite, augite-diorite with hornblende, and augite-diorite with enstatite.

On the east side of the estuary of the Cree, about 2·5 km south of Creetown, a dyke-like mass of granodiorite trends east-north-east. Quarries in this intrusion show a prominent series of north-north-westerly joints resembling a large-scale fracture-cleavage, which may have been caused, according to Blyth, by relative movement of the walls of the intrusion.

Radiometric age-determinations carried out on specimens from a large granite dyke at Creetown gave the following results: K/A method 390 ± 12 m.y.; Rb/Sr 388 ± 19 and 410 ± 20 m.y. These ages are close to that assigned to the Siluro–Devonian boundary.

As already mentioned, one of the characteristic features of Lower Old Red Sandstone igneous activity is the prevalence of a similar magma over a wide area. In the south-west, as in the north-east, all the plutonic rocks are intimately related, and the occurrence of the same types in widely separated localities suggests that they belong to the same petrographical province. While the various rocks of the plutonic masses probably originated by differentiation of the same magma, it is believed by some authors, for example Gardiner, Reynolds and Deer, that, in complexes like those at Loch Doon and Cairnsmore of Carsphairn, each of the constituent rock-types represents a separate intrusion, the emplacement taking place in order of increasing acidity. Others, however, such as Higazy, favour a metasomatic mode of origin for the rocks of the Loch Doon complex. Malcolm MacGregor, as a result of his work on the western part of the Criffell complex, came to the conclusion that the Bengairn quartz-diorite was the result of a transformation of hornfelses by a process of granitization.

Dykes are extremely abundant in the Galloway district and especially so in the neighbourhood of the Criffell and Loch Doon masses, where they cut both the plutonic rocks and the surrounding sediments. The western end of the Criffell complex is cut by numerous dykes with a north-westerly trend, which are mainly porphyrites with a few lamprophyric types. The minor intrusive rocks associated with the Loch Doon pluton fall into three groups: (1) acid rocks, such as aplites, granite-porphyries, granophyres, micro-granites and orthophyres; (2) porphyrites, and (3) diorites and lamprophyres. Thermally metamorphosed dykes have been recorded in the aureoles of the Loch Doon, Cairnsmore of Fleet and Portencorkrie masses.

The Ordovician and Silurian rocks of Wigtownshire are cut by many dykes, described by Read, which range in composition from feldspathic varieties to lamprophyres. A group of sheared dykes, mainly porphyrites, trending east-north-east, is found in the area between Creetown and Gatehouse-of-Fleet, but in Galloway as a whole the dominant trend of the dykes is north-easterly,

and the majority consist of rocks to which the term porphyrite has been applied. In typical rocks of the group phenocrysts of plagioclase, hornblende and biotite are found in a compact groundmass of the same minerals, associated with quartz and alkali feldspar. The rocks vary in colour from grey to red, the latter tint being characteristic of the most highly altered varieties. The diorite dykes are usually dark-coloured crystalline rocks essentially composed of hornblende and plagioclase feldspar. The lamprophyre dykes of Galloway include malchites, spessartites and kersantites.

Dykes similar to those described above occur scattered throughout the eastern part of the district. Quartz-porphyry and lamprophyre dykes trending north-eastwards occur in association with the Cockburn Law intrusion. The Priestlaw mass is cut by several dykes of decomposed porphyrite and the Lamberton Beach intrusion is intersected by a lamprophyre dyke.

The metamorphism resulting from the emplacement of granitic material into the surrounding sedimentary rocks varies widely in amount and intensity. Thus, narrow dykes have generally effected little or no alteration in the adjacent strata, but around the margins of such large masses as those of Criffell, Loch Doon and Cairnsmore of Fleet great alteration has been produced; a broad ring of metamorphosed sediments surrounds the intrusions. In Galloway the altered rocks comprise greywackes, grey and black shales, cherts, Ordovician igneous rocks, and dykes of Old Red Sandstone age. Characteristic minerals resulting from the metamorphism are biotite and garnet, while cordierite is also plentiful in the inner parts of the metamorphic aureoles of the Loch Doon and Cairnsmore of Carsphairn masses. The greywackes are characterized by the development of abundant brown biotite, while flaggy beds sometimes pass into a dark hornfels containing cordierite. Highly metamorphosed sediments occur at Knocknairling Hill, about 2 km west of New Galloway, where argillaceous rocks pass into andalusite-mica-schists, and gritty beds become quartz-mica-schists. Corundum, sometimes with the dark blue colour of sapphire, has been noted in highly metamorphosed sediments at Buchan Hill, Loch Trool, in the aureole of the Loch Doon mass, at Bennan Hill near the north-east end of the Cairnsmore of Fleet intrusion, and at Broad Law.

Upper Old Red Sandstone

The extent of the denudation which took place in the interval between the deposition of the Lower and the Upper Old Red Sandstone is indicated by the disconnected nature of the remnants of the earlier formation. In Upper Old Red Sandstone times according to Wills the south-western part of the region probably continued to project as a land-mass, while much of the remainder formed part of the North British Cuvette. In the Eyemouth district the deposits of the Upper Old Red Sandstone rest with marked discordance on the Lower Old Red Sandstone, and in parts of Roxburghshire they lie on the Cheviot lavas, but elsewhere these beds repose on an uneven floor of folded Ordovician and Silurian rocks.

From the vicinity of Greenlaw to the Jedburgh area the Upper Old Red Sandstone occupies a tract of undulating country. Near the former locality the succession appears to be divisible into two groups, a lower formed largely of conglomerates and an upper composed of interbedded red sandstones and

marls. In the Jedburgh district the greater part of the formation is composed of soft and crumbly dark red and brown arenaceous and marly beds with sandstone ribs. Thicker beds of red and white sandstone occur throughout the succession, with conglomerates and conglomeratic sandstones in the basal part. The conglomerates are composed mainly of greywacke pebbles, with scattered fragments of porphyrites and other igneous rocks derived from minor intrusions in the Lower Palaeozoic. Wind-rounded sand grains in the sandstones seem to indicate a semi-arid continental climate. Sun-cracked surfaces are a common feature and indicate periodic desiccation.

To the south-west of Jedburgh the outcrop narrows and the formation continues as a faulted strip towards Riccarton and Langholm. In the last-mentioned district the rocks are predominantly red sandstones, in part pebbly, and a coarse conglomerate of Silurian fragments is normally present at the base; the thickness of the formation ranges from 15 to 180 m. Five kilometres west-south-west of Langholm another narrow belt of Upper Old Red Sandstone crops out from beneath the Birrenswark Lavas and extends south-westwards to the railway midway between Lockerbie and Ecclefechan, where it passes beneath a small patch of 'Permian'. On the west side of the Nith the formation is represented in the Kirkbean district by a thin development of conglomerate, siltstone, shale and sandstone.

At the northern end of the outcrop, near Lauder, conglomerates and sandstone extend as a narrow tongue up the Leader Valley to New Channelkirk. The main outcrop, however, swings to the north-east towards Duns and then eastwards towards Berwick, forming the western and northern boundaries of the Merse of Berwickshire. From the vicinity of Duns a branch of the outcrop passes northwards through the Lammermuir Hills to join the Upper Old Red Sandstone outcrop which borders the Carboniferous basin south of Dunbar on its western and southern sides. On the south-east side of the Lammermuir Fault near Fala and Gifford there are two patches of Upper Old Red Sandstone. The lowest member of the succession in both areas is a conglomerate consisting of rolled fragments of greywacke. It is followed in the Gifford valley by red sandstones and red micaceous marls, while south-east of Fala a more variegated set of sandstones occurs, and the coarser grits include small fragments of chert.

There is evidence that the Upper Old Red Sandstone originally covered a greater area than it at present occupies. It is probable, for instance, that much of the eastern part of the Lammermuir Hills was at one time overlain by Upper Old Red Sandstone conglomerates and sandstones, since the conglomerate ascends to a height of over 410 m on Monynut Edge, and several outliers occur between St. Abb's Head and Berwick. The formation crops out on the lower slopes of the Eildon Hills, near Melrose, and several other outlying patches are found in the area between Melrose and Selkirk, while on Tudhope Hill, east of Mosspaul, a large block of Upper Old Red Sandstone is preserved in the agglomerate infilling a volcanic neck.

The sections in the Jed Water, near Jedburgh, and at Siccar Point, about 4 km east of Cockburnspath, are of historical interest. They were visited and described by Hutton, and his studies of the highly inclined Silurian rocks overlain by nearly horizontal sandstones and marls of the Upper Old Red Sandstone were the means of establishing some of the fundamental principles of geology.

The upper part of the formation, in which the colour is generally less red, is characterized by the occurrence of irregular masses of cornstone. Bands and lenses of chert have been noted in this part of the succession near Cockburnspath and in the Riccarton area. The fact that similar calcareous rocks are found in the Upper Old Red Sandstone and in the lower beds of the overlying Carboniferous makes it difficult to separate the two formations where fossil evidence is lacking.

Two rich fish-beds recently found in the grounds of Duns Castle have yielded *Bothriolepis* and *Holoptychius*. Scales of *Holoptychius* have been collected at several other localities within the region, and plates of *Bothriolepis obesa* have been recorded from the Jedburgh and Chirnside areas.

A number of isolated exposures of igneous rocks to the west and south-west of Greenlaw have in the past been mapped as lavas intercalated in the Upper Old Red Sandstone, but the investigations of A. G. MacGregor and Eckford have shown them to be intrusions.

Two lavas, interbedded with red marls and cornstones, recorded in a boring for water at Stonefold, near Greenlaw, have been referred by Manson and Phemister to the Upper Old Red Sandstone. These are olivine-basalts of Dalmeny type, similar to those of the Kelso volcanic series at the base of the Carboniferous. It is possible that they represent an early effusion of the same series, but in view of the difficulties in separating the Upper Old Red Sandstone from the Carboniferous the question of age cannot be regarded as settled.

PLATE VI

A. Lower Old Red Sandstone volcanic rocks at Horsecastle Bay, St. Abbs, Berwickshire. Two andesitic lava flows separated by water-laid tuffaceous grits and sandstones. The irregular base of the upper flow is clearly displayed. (Geol. Surv. Photo. No. D1229).

B. Criffell Granite, Kirkcudbrightshire. Southwards view of Criffell (569 m) from north of New Abbey. The porphyritic division of the main granodiorite forms the wooded ridges on the right (Fig. 12); the non-porphyritic division crops out over the remainder of the area in the photograph. (Geol. Surv. Photo. No. C3583).

A

B

6. CARBONIFEROUS

The Carboniferous System is well developed in the South of Scotland but strata representing the whole sequence are present only in one small area near Langholm, where there are some 3500 m of beds. They include rocks greatly varied in character, ranging from thick beds of sandstone, mudstone and limestone to thinner developments of coal, seatclay, ironstone and cementstone, together with basalts and tuffs of volcanic origin. Elsewhere in various disconnected outcrops throughout the district only parts of the sequence are present. Nevertheless the evidence is sufficiently complete for most of the history of deposition and erosion, earth-movement and volcanic action to be understood.

Throughout Britain a threefold classification of the Carboniferous System, based mainly on lithology, has been adopted. The Carboniferous Limestone Series at the bottom is succeeded by the Millstone Grit Series which, in turn, passes up into the Coal Measures. Although the lithological differences are less marked in the South of Scotland the three divisions have been recognized because broad correlations can readily be made with other districts from studies of the varied fossil assemblages found in the rocks.

The most westerly outcrop is a narrow strip of strata of Millstone Grit Series age along the western margin of the outlier of New Red Sandstone rocks around Loch Ryan (Fig. 13). Two prominent outliers occupy much of the valley of the River Nith. In the more northerly, around Sanquhar and Kirkconnel, the beds are mostly of Coal Measures age. Small thicknesses of both Carboniferous Limestone Series and Millstone Grit Series are present below an unconformity. In a small outlier a few kilometres to the north-east in the valley of the Duneaton Water adjacent to the Southern Upland Fault much of the Carboniferous sequence is represented in a thin development. Around Thornhill the strata are mostly red and are concealed in places below basaltic lavas and sandstones of New Red Sandstone age. Nevertheless rocks of both Carboniferous Limestone Series and Coal Measures age have been recognized with certainty. No evidence has been found as yet that Carboniferous rocks are present below the New Red Sandstone around Dumfries, Lochmaben and Moffat.

The largest outcrop of Carboniferous strata extends north-eastwards for about 130 km from Kirkcudbright to the Cheviot Hills. It fringes the great areas of Carboniferous outcrop in the northern counties of England to the south. The beds are mostly of Carboniferous Limestone Series age but the Millstone Grit Series and Coal Measures are well represented in a small area around Canonbie on the River Esk. There is no doubt that Carboniferous rocks are present below the New Red Sandstone outcrop around Kirkpatrick but the age of these beds is unknown. Around Kelso and north-eastwards to the coast south of Eyemouth basaltic rocks and sediments of Carboniferous Limestone Series age crop out but they are not well seen because of lack of

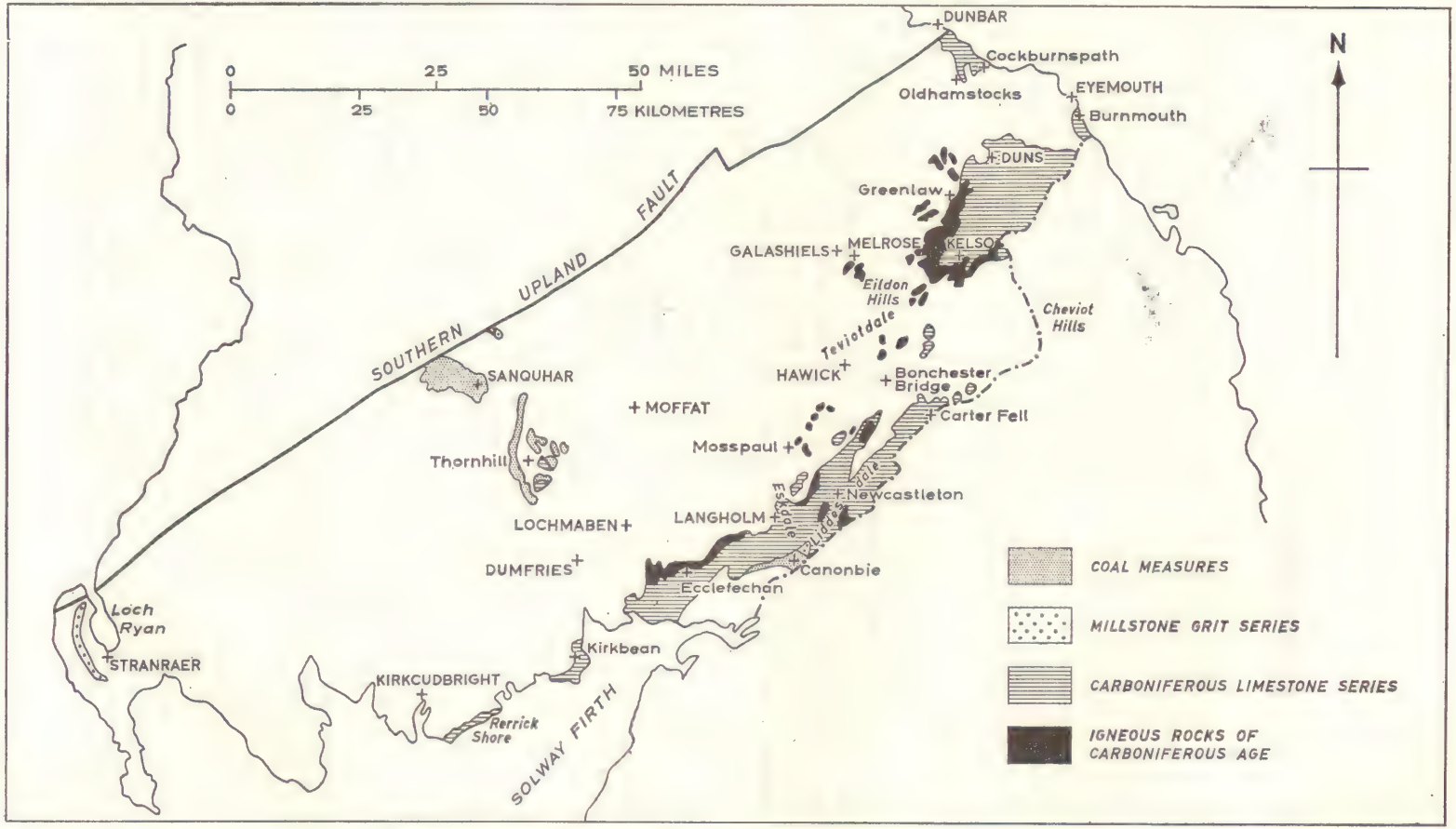


FIG. 13. *Outcrops of Carboniferous rocks in the South of Scotland*

exposure. A further small outcrop of strata of similar age occurs along the coast from Dunbar south-eastwards to Cockburnspath.

Outside the principal areas of outcrop there are numerous remnants of ancient volcanoes which are thought to have been active during Carboniferous times. These small outcrops of igneous rock intruded into strata of Silurian and Upper Old Red Sandstone age are mostly scattered over the district between Langholm and Duns.

Apart from strata of various lithologies which have been quarried for building-stone and roadstone the Carboniferous rocks which have so far proved to be of economic value in the South of Scotland are coal and limestone. In the sequence coals occur mainly in the Coal Measures with the result that the coal industry has developed round Sanquhar and Canonbie. No coal has been worked at Thornhill because such coal seams as were in the sequence there have been chemically altered during a secondary process of oxidation. Limestones of workable thickness are developed mainly in the upper part of the Carboniferous Limestone Series. Consequently, although many beds have been quarried over much of the outcrop for local agricultural purposes, limestones are at present being worked only near Canonbie and, on a larger scale, south-east of Dunbar (Plate X).

History of Deposition

The true base of the Carboniferous System has not been established anywhere in the south of Scotland. An arbitrary base has been chosen in each district at a convenient and mappable horizon below the lowest beds which are known from their fossil content to be undoubtedly Carboniferous in age. The base is therefore at a lithological boundary and, since lithology is seldom a criterion of age, the chosen base is not necessarily at the same horizon from district to district. It may be also that some or all of the underlying Upper Old Red Sandstone strata should be included in the Carboniferous. There is doubt about the age of these beds but, because they do not contain a diagnostic fauna and because their lithology differs in detail from that of younger strata, they have not hitherto been regarded as part of the Carboniferous.

Along the southern flank of the Southern Uplands a great outburst of volcanic activity is taken to mark the beginning of the Carboniferous period. Whether the beginning of the volcanic episode was everywhere contemporaneous has not been established but numerous flows of basaltic lavas of similar nature were deposited over the whole area from the Solway Firth to Berwickshire at about the same time. In the south-west they are called the Birrenswark Lavas and farther to the north-east the local name is the Kelso Traps. In the Cockburnspath area there is a transition from sediments assigned to the Upper Old Red Sandstone to Carboniferous sediments with no evidence of volcanic activity at that time. Elsewhere the Carboniferous rests unconformably on Silurian and Ordovician strata and because of successive overlap the beds immediately above the unconformity are of different ages from place to place.

Following the volcanic activity in the southern districts great thicknesses of sediments were laid down in the slowly subsiding Northumbrian Trough. Sandstones and mudstones constitute the bulk of the sequence. These are of deltaic and fluvial origin and were deposited in shallow water between the

principal land mass to the north and the open sea to the south. Thin bands of cementstone are common in the lower beds of the Carboniferous Limestone Series. They suggest the frequent recurrence of lagoonal conditions with wide estuarine flats submerged in shallow water undisturbed by violent movement. The presence of sun-cracks and rain-pits in associated beds make it clear that there was periodic emergence of the top of the sediments above water-level. Higher in the sequence, although sandstones and mudstones are still predominant, the cementstones give way to highly fossiliferous calcareous mudstones and limestones resulting from recurring marine incursions. At the same time thin coals and beds containing roots appear in the sequence showing that there were periods of emergence sufficiently prolonged to allow the establishment of vegetation. The marine beds, coals and rooty beds are more prominent in the upper part of the Carboniferous Limestone Series, where the succession is distinctly of cyclic Yoredale type. The strata were clearly laid down during rapid alternations between terrestrial and deltaic conditions and truly shallow marine conditions.

During the first half of the time during which the sediments were deposited volcanic activity was sporadic and apparently confined to south-east Scotland. The volcanic province was roughly triangular, lying to the south of a line from Dumfries to Dunbar. The evidence of volcanic activity which has been preserved is diverse and includes extensive flows of basaltic lava and beds of tuff interbedded with the sediments, remnants of many old volcanoes from which the lavas and tuffs were extruded, and various intrusive bodies of acid and basic igneous rocks. The first outburst at the beginning of Carboniferous Limestone Series times appears to have been the most extensive. Almost the whole province was covered at about the same time by the Birrenswark Lavas and Kelso Traps, interdigitating flows of basalt with a cumulative thickness seldom less than 15 m and reaching up to 120 m. Some time later there was renewed but local activity over a small area just to the east of Langholm during which the Kershopefoot Basalt was laid down. The latest extrusive activity was over a somewhat greater area mainly in Eskdale and Liddesdale. At this time the tuffs and tuffaceous sediments with minor lava flows, collectively known as the Glencartholm Volcanic Beds, were deposited while the area was covered by a shallow sea. Far to the east, at Oldhamstocks in the Dunbar outcrop, lavas with subsidiary beds of tuff are present amongst Carboniferous sediments. They are thought to be limited in extent and their age is uncertain although they may be associated with the Garleton Hills Volcanic Rocks of East Lothian. The ages of the scattered volcanic vents and intrusions can be implied only from the knowledge that none of them has been intruded into beds later than early Carboniferous Limestone Series. It seems likely, therefore, that the emplacement of the intrusions was contemporaneous with the extrusion of the lavas and that activity in the province became extinct in early Carboniferous times.

The Millstone Grit Series is the part of the Carboniferous sequence which is least well known. Strata of this age are known only near Loch Ryan, around Sanquhar and Thornhill and to the south of Langholm in Dumfriesshire. They are so poorly exposed near Loch Ryan that neither the sequence nor the precise age has been established. Around Sanquhar and Thornhill the beds are less than 30 m thick. Although the age of some of the strata is in doubt there is evidence of unconformities and non-sequences amongst the beds

suggesting that they were deposited during a period of instability when there were several episodes of earth-movement. The only volcanic activity known at this time was around Loch Ryan where a thin basaltic lava was deposited. The most complete sequence of sediments is south of Langholm where the total thickness is thought to be about 430 m. Even in this area the details of the higher beds are not well known. The lowest strata are a continuation of the rhythmic Yoredale facies of the underlying Carboniferous Limestone Series. At this time the environment was predominantly marine with the area covered almost continuously by a shallow sea. There are few coals or rooty beds in the sequence suggesting that emergence was infrequent and short-lived. This was followed by a period of deltaic deposition during which a sequence composed predominantly of sandstones accumulated. There were frequent periods of vegetation as shown by the numerous rooty seatearths and thin coals. Thin marine bands show that marine incursions were common but relatively short-lived. Similar conditions continued until the end of Millstone Grit Series times. A greater development of thin coals and rooty beds indicates that the depositional surface was about or above water level much of the time. No shells have been found in these strata suggesting that the sea did not invade the district at any time during this period. Near the top of the sequence some secondary reddening of the strata has taken place. This is attributed to oxidation of grey strata below a land surface and is probably related to a period of uplift and erosion which took place before the younger Coal Measures rocks were deposited unconformably.

Beds of Coal Measures age have been preserved only in the Sanquhar and Thornhill outliers and in a small area south of Langholm. Although similar ranges of strata are present in all three areas thicknesses range from 180 m at Thornhill to 600 m at Sanquhar and over 900 m south of Langholm. The basal beds of the Coal Measures appear to be absent everywhere. In places around Sanquhar and Thornhill strata of the lowest non-marine bivalve zone, the *Anthraconaia lenisulcata* Zone, have been deposited disconformably or after a non-sequence on beds of the Millstone Grit Series. Widespread deposition did not take place, however, until much later during *Carbonicola communis* Zone times. In the area south of Langholm the earliest known Coal Measures strata, containing a fauna indicative of the lower part of the *Anthraconaia modiolaris* Zone, rest with angular discordance on older beds. The sediments were laid down in cyclic sequences of variable thickness. A typical lithological sequence in ascending order is: coal, carbonaceous shale with plant remains and fish debris, mudstone with non-marine bivalves (mussels), siltstone, sandstone, seatearth with roots, coal. These beds are freshwater or brackish in origin and the environment was one of shallow water except during the numerous periods when vegetation was established on sediments at or above water-level giving rise to the many coal seams and rooty beds in the sequence. A number of the coals, from 0·6 to 4·6 m thick, have proved to be workable and have been mined extensively underground and at outcrop in the Sanquhar outlier and to a lesser extent in the Canonbie Coalfield south of Langholm. In the latter area considerable reserves remain intact at depths up to 600 m in a concealed coalfield. In common with most other areas in Britain there are several thin beds of mudstone with marine faunas in the lower part of the sequence, evidence of widespread but short-lived marine transgressions.

At Sanquhar and south of Langholm the lower beds of the Coal Measures are grey, but the upper beds in these areas and all the strata of this age at Thornhill are red and purple as a result of the oxidation of their iron content. The reddening is thought to have taken place in a semi-arid climate during an interval between Carboniferous and New Red Sandstone sedimentation. The depth to which beds have been reddened completely and partially is considered to have been controlled by the level of the pre-New Red Sandstone water-table. The process of oxidation has altered the character of some of the fine-grained sediments. The bedding in shales and mudstones has, in places, completely disappeared and has been replaced by pseudobrecciation which is accentuated by variations in colour. In seatearths all the carbonaceous material has been altered, leaving only vestiges of roots here and there. Coal seams have been destroyed leaving only thin bands of deep-brown irony rubble. This is particularly important at Thornhill where the whole of the attenuated sequence has been oxidised and, as a result, no coal has been recorded although coal-positions are clearly seen in a normal cyclic development. In association with the reddening some coals in the area south of Langholm have been replaced totally or to some degree by dolomitic limestone.

Towards the end of Carboniferous times and before the deposition of the earliest New Red Sandstone strata there was a period of non-deposition while the Carboniferous and older rocks of the South of Scotland were folded and faulted by the earth-movements of the Armorican orogeny. The only evidence of the last phase, the Borcovician movements, are a few quartz-dolerite dykes intruded into the sediments with east–west orientation.

Fossil Record and Age of Strata

Many of the strata, particularly the shales and limestones, contain plant and animal fossils. They are so abundant in some beds that much of the rock is composed of their remains. Some research has been carried out on the plant fossils of this area but it is from the identification of individual marine shells and the correlation of faunal assemblages that ages of the sedimentary strata have been worked out.

The oldest fossiliferous beds occur in Liddesdale to the east of Langholm where the fauna is predominantly composed of the calcareous-tubed worm *Serpula*, the bivalve *Modiolus latus* and ostracods. In some beds these fossils occur in great profusion. This type of assemblage represents the so-called 'Modiola-phase' of the Carboniferous in Britain, which seems to be associated with the first invasions of the sea over an area when conditions were such that only a few organisms could tolerate them. The beds and their faunas became more marine upwards and the earliest occurrence of a typical Carboniferous shelly fauna is a rich marine assemblage including corals, bryozoa, *Cleiothyridina glabristria*, orthotetoids, productoids, *Syringothyris* and marine molluscs. Locally, in the Langholm area, great developments of rock-forming algae are associated with these faunas. Only one marine band, that containing specimens of the brachiopod *Syringothyris* cf. *cuspidata* and locally called the Harden Beds, has been recognized over a widespread area. Occurrences have been recorded on the Rerrick shore, in the Kirkbean outcrop, near Ecclefechan, in Liddesdale and in the Bewcastle district of the north of England.

The age of the early Carboniferous strata is difficult to establish. The species which are diagnostic of the Tournaisian coral-brachiopod zones of the South-West Province of England are absent and, as a result, the shelly faunas present suggest only an approximate age of upper Tournaisian or early Viséan. Recent work on ostracods has suggested a Tournaisain age for strata in the north of England which can clearly be correlated with beds near the bottom of the succession in the south of Scotland.

Along the Solway Firth and eastwards to the Cheviot Hills the upper half of the Carboniferous Limestone Series has an abundant rich marine fauna consisting mainly of corals, brachiopods and bivalves. In the lower beds several species of *Lithostrotion*, trepostomatous bryozoa and Gigantoproductids are particularly prominent. Somewhat higher in the sequence, in strata locally called the Dinwoodie Beds, a large number of new forms appear for the first time in the fauna. They include *Lithostrotion junceum*, *Giganto-productus* cf. *latissimus*, *Leptagonia* [*Leptaena*] cf. *analoga*, *Plicochonetes*, *Tornquistia* and *Actinopteria persulcata*. In the uppermost beds the limestones contain a rich fauna mainly of corals and brachiopods and the associated roof-shales contain mainly brachiopods and molluscs. The corals include *Aulophyllum*, *Dibunophyllum* and several species of *Lithostrotion*. Productoids are common, particularly *Eomarginifera* and Gigantoproductids of both latissimoid and giganteid form. There is no doubt that all these faunas are of Viséan age and there are sufficient diagnostic forms present to show that the coral-brachiopod zones C_2S_1, S_2, D_1 and D_2 are represented. No significant goniatite evidence has been found but the presence of the bivalve *Posidonia becheri* in strata near the top of the sequence shows that these beds at least are of P_1 age.

In the Sanquhar and Thornhill outliers only a few fossiliferous bands have been found. These have yielded poor faunas consisting mainly of brachiopods and bivalves which indicate that the strata are upper Viséan in age.

In the Berwickshire and Dunbar to Cockburnspath outcrops most of the Carboniferous Limestone Series is poorly fossiliferous and contains no marine bands. The correlation of these beds is based on lithology and, while they are thought to be mainly Viséan in age, some Tournaisian strata may be present by analogy with neighbouring sequences in the north of England. The earliest marine bands, present on the coast at Cove and in neighbouring streams, contain mainly brachiopods and bivalves. These bands are thought to be of the same age as the Dun and Woodend limestones of Berwickshire and the Redesdale Ironstone and Limestone of Northumberland. The coral-brachiopod assemblage suggests a D_1 age and the presence of *Beyrichoceratoides redesdalensis* suggests that the goniatite zone B is represented. The topmost beds of the Carboniferous Limestone Series, outcropping on the shore south of Dunbar, are much more fossiliferous with assemblages very similar to those of beds of the same age around Langholm. Corals are particularly abundant, *Saccamminopsis fusulinaformis* is strikingly developed in bands and numerous weathered surfaces are crowded with 'cauda-galli' markings. There is no doubt about the upper Viséan age of these beds.

During Millstone Grit Series times the environment became progressively less marine. Consequently the most abundant marine faunas are found only in the lowest beds and these are essentially an impoverished continuation of those found in the underlying Carboniferous Limestone Series. In the

Langholm area the bulk of the fauna is brachiopods and bivalves including *Eomarginifera*, Gigantoproductids of latissimoid form and *Streblopteria ornata*. In the higher beds plant remains are more common and, apart from a few thin limestones with shelly faunas, animal fossils are restricted to thin shale bands containing mainly *Lingula* and *Orbiculoidea*. The precise age of all the strata is uncertain. No diagnostic goniatites have been found and so the Namurian goniatite stages have not been established. Nevertheless, by comparison with other areas, there is no doubt that at least the two lowest stages, E_1 and E_2, are represented. In the Stranraer outcrop the only fossils recorded are plants and no precise age is known for the strata. At Thornhill the fauna is mostly poorly preserved brachiopods and bivalves from which it has been suggested that the strata are probably of E_2 age. In the Sanquhar outlier two marine bands have yielded mainly brachiopods from which an E_2 age has been deduced for all the strata. Recent work on plant spores, however, has suggested that beds of E_1 age are present and that the uppermost strata included in the Millstone Grit Series may rather be of Westphalian A age.

In the Coal Measures many bands carry fossils which are mainly non-marine bivalves or mussels of the genera *Anthraconaia*, *Anthraconauta*, *Anthracosia*, *Anthracosphaerium*, *Carbonicola*, *Curvirimula* and *Naiadites*. The non-marine bivalve zones known to be present are (in ascending order): *Anthraconaia lenisulcata* Zone, *Carbonicola communis* Zone, *Anthraconaia modiolaris* Zone, Lower *Anthracosia similis–Anthraconaia pulchra* Zone, Upper *A. similis–A. pulchra* Zone, *Anthraconauta phillipsii* Zone and *Anthraconauta tenuis* Zone. All the zones except the topmost have been recognized with certainty in the Sanquhar outlier but in the neighbouring outcrop around Thornhill only the *C. communis*, *A. modiolaris* and Lower *A. similis–A. pulchra* zones are known to be present. At Canonbie all the upper zones are well represented but the first Coal Measures deposits resting unconformably on older strata are of late *A. modiolaris* age. Ostracods and *Spirorbis* are associated with the mussels in some bands and the latter occurs in freshwater limestones in the upper part of the sequence. Fragmentary fish remains are common, particularly in beds immediately overlying the coals. Specimens of '*Estheria*' are abundant in beds which are mostly associated with the marine bands of the sequence. Marine faunas are restricted to a few bands which occur mainly near the bottom of the sequence and in the Lower and Upper *A. similis–A. pulchra* zones. The forms present are mostly foraminifera, *Lingula*, *Orbiculoidea* and the trace-fossil *Planolites ophthalmoides*, but brachiopods and bivalves are abundant in Skipsey's Marine Band of Sanquhar and a distinguishing feature of the Skelton Marine Band of Canonbie is the presence of conodonts.

Extent of Deposits

In the South of Scotland the area of deposition became more and more extensive during Carboniferous times. The earliest known deposits, the Birrenswark Lavas and Kelso Traps, were laid down over an area probably little more extensive than that of the present outcrops from Kirkbean on the Solway Firth eastwards to the Cheviot Hills and around Kelso (Fig. 13). They do not extend far south into England and are not present in the sequence

at Loch Ryan, in the most westerly outcrops on the Solway Firth, at Sanquhar and Thornhill and on the coast southwards from Dunbar. The earliest sediments fringe the southern and eastern margins of the Southern Uplands and in places there are local indications of proximity to the edge of the depositional basin. The coarse-grained strata along the Kirkcudbrightshire coast appear to be marginal facies. From Dumfries north-eastwards to the Cheviot Hills there are bodies of sandstone which appear to represent the deposition in local deltas along the northern margin of the slowly subsiding Northumbrian Trough. It is less easy to define the margin of deposition farther to the east. The earliest deposits in Berwickshire and south of Dunbar were clearly in shallow water. Nevertheless this type of environment may have been extensive. The presence of debris of Carboniferous lithology in some vents shows that the original deposition extended some way beyond the limits of the present outcrops. It would appear, therefore, that in Tournaisian or early Viséan times deposition was confined to areas south and east of a line from Kirkcudbright to Hawick and northwards through Galashiels.

Deposition extended farther northwards only in late Viséan times as is shown by the Carboniferous Limestone Series strata at Thornhill and Sanquhar. It seems likely that at the same time the Midland Valley basin of deposition extended southwards to encroach upon the Southern Uplands because the strata at Sanquhar and the north end of the Thornhill outlier are similar in lithology and fauna to the development in neighbouring areas to the north. The extent of these deposits is uncertain since nowhere has a marginal facies been preserved. The extremely thin developments at Sanquhar and Thornhill, however, suggest that in the eastern part of the Southern Uplands the overlap of these younger beds beyond the limits of deposition of the earliest Carboniferous strata may have been patchy. There is no evidence of deposition at this time over the western part of the Southern Uplands.

The presence of beds of Millstone Grit Series age near Loch Ryan shows that there was a further extension of the depositional area during that period. The thin developments there and at Sanquhar and Thornhill suggest again that the main depositional areas lay along the southern and eastern flanks of the Southern Uplands and that elsewhere in the region deposition was slight and patchy.

Most of the evidence of deposition during Coal Measures times has been removed by subsequent erosion. It is assumed that there was widespread deposition in fairly stable conditions in common with much of Europe. Nevertheless it is clear that there was no deposition at the beginning of this period in the area to the south of Langholm where the earliest Coal Measures recorded are of *A. modiolaris* Zone age. Although early Coal Measures are thin in both the Sanquhar and Thornhill outliers, the upper parts of the Coal Measures sequence are fully represented there and at Canonbie. The strata at Sanquhar are closely related to those farther north in adjacent areas of the Midland Valley and there is a great thinning south-eastwards to Thornhill. It may be, therefore, that in the south of Scotland the Coal Measures were deposited in at least two separate basins, one in the north associated with the Midland Valley and one in the south linked with the north of England, and that some parts at least of the Southern Uplands remained free of deposition.

Loch Ryan

A narrow outcrop of strata thought to be of Upper Carboniferous age extends southwards for about 16 km from Jamieson's Point. The rocks are poorly exposed but it is clear that they rest unconformably on Ordovician strata and are in turn overlain unconformably by breccias of New Red Sandstone age. They consist of grey, red and mottled sandstones with beds of purplish grey shale and seatclay. One thin flow of basaltic lava has been noted in the sequence. The strata probably represent part of the Millstone Grit Series. The only fossils recorded so far are plants from shales cropping out in the Craigoch Burn. A thin bed of kaolinitic rooty clay crops out near Low Knockglass to the south-west of Stranraer.

Sanquhar

The Sanquhar outlier in the valley of the River Nith comprises a rectangular outcrop of about 45 square kilometres in which the rocks at the surface are mainly Upper Carboniferous, together with several smaller detached outcrops in which strata mainly of Lower Carboniferous age have been preserved. To the north-west the outlier lies adjacent to the Southern Upland Fault and the north-eastern margin is clearly marked by an abrupt change of slope across a fault intrusion separating Carboniferous and Ordovician strata. Elsewhere the margin is the outcrop of the unconformable junction between Carboniferous and older strata. The towns of Sanquhar and Kirkconnel have grown up around the mines in which several coals in the sequence have been worked, an industry which is now dying rapidly.

Structurally the outlier comprises two adjacent faulted basins. The western part is a shallow syncline plunging gently to the north-east while the eastern part is a much-faulted basin parallel to the elongation of the outlier. In Coal Measures times the main depositional basin appears to have been orientated north-westwards and probably lay near the line of the present north-eastern boundary fault. The strata are heavily faulted, the dominant trend being north-west. Many of the fractures have throws of only a few metres, several have throws of over a hundred metres and the calculated displacement across the boundary fault is at least 550 m in places. The strata have been further disrupted by the intrusion of numerous thin dykes of doleritic rock during the Tertiary period.

The Carboniferous Limestone Series is represented by about 10 m of mudstones, siltstones, sandstones, seatclays and thin argillaceous limestones, which rest unconformably on Ordovician strata and are in turn overlain unconformably by younger Carboniferous strata. These beds are restricted to the eastern part of the outlier where they are best seen in Howat's Burn. Marine fossils are common in most of the strata with assemblages consisting mainly of brachiopods and bivalves of upper Viséan age. Some of the strata have yielded plant spores which have been compared with those from strata of the P_2 goniatite zone elsewhere.

Strata referred to the Millstone Grit Series have a maximum thickness of just under 30 m. They occur in a number of disconnected outcrops on the western and southern margins of the outlier where they rest unconformably on Ordovician strata. The most extensive sections are exposed in the Polhote and Polneul burns. Much of the sequence is composed of sandstones, many

of which are coarse-grained with irregular bases suggesting several periods of erosion and subsequent non-sequence in the deposition. Near the base there is a widespread occurrence of an unusual development of kaolinitic sandstone about 2 m thick. Interbedded with the sandstones are a few thin beds of mudstone, siltstone and rooty seatclay. The fauna is restricted to two marine bands. The lower, the Polhote Marine Band, is up to 1·2 m in thickness and contains predominantly bivalves together with brachiopods and gastropods. The macrofaunal assemblage is not diagnostic but it seems to indicate an E_2 age in terms of the Namurian goniatite zones. The upper band, Tait's Marine Band, is a bed of dark grey mudstone up to 1·8 m thick which was first described from a good exposure at the junction between Macan's Burn and the Polneul Burn. In the southern part of the outlier it yields a rich marine fauna mainly of brachiopods. Farther north and west the fauna is restricted to *Lingula* and *Orbiculoidea*. The evidence as to the age of the marine band is conflicting in that the shelly brachiopod assemblage suggests an E_2 age whereas spores collected from associated strata indicate that they may be of Westphalian A age and should be more properly included in the Lower Coal Measures.

A marked faunal change occurs above Tait's Marine Band. It is associated with a plane of angular discordance in places and there is a marked eastward overlap by the earliest beds of the Coal Measures. In common with the Midland Valley the Coal Measures, which are about 600 m thick, have been divided into Lower, Middle and Upper Coal Measures (Fig. 15). The lower limit of the Middle Coal Measures is taken at the base of the Queenslie Marine Band and the upper limit at the top of Skipsey's Marine Band.

The Lower Coal Measures, totalling some 120 m of strata, are mainly sandstones with a few thin coals in the lower part while the upper part is typical Coal Measures cyclic development of sandstones, siltstones, mudstones, coals and seatclays. No diagnostic non-marine bivalve faunas have been recorded from the lower beds but the presence of two marine bands yielding *Lingula mytilloides* suggests that some of these beds at least belong to the *A. lenisulcata* Zone. Numerous boreholes have shown that the upper beds are characterized by a group of coals, the Swallowcraig Coals, which have proved to be of little value because of their great variation in number and thickness. Shortly below them occurs a persistent mussel band containing abundant specimens of *Carbonicola communis*, *C. pseudorobusta* and *C. robusta* which, together with the associated fauna, represent a typical assemblage of the *C. communis* Zone. A prominent mussel band just above the coals contains numerous forms of *Anthracosia* typical of the lower part of the *A. modiolaris* Zone. The only coal which has been mined extensively is the Kirkconnel Splint which occurs near the top of the group. Mussels, including specimens of *Anthraconaia modiolaris*, are commonly found in the roof-beds.

The Middle Coal Measures, some 120 m thick, are typically cyclic in their development throughout. They contain two persistent thick coals, the Creepie and the Calmstone, together with a number of thinner seams. Mussels occur in many of the mudstone beds overlying the coals. Assemblages indicative of the *A. modiolaris* Zone have been found in the lower part of the sequence while the upper part contains faunas of Lower *A. similis–A. pulchra* Zone age. Two distinctive bands have been noted. The lower including *Anthraconaia salteri* in its assemblage lies just above the Parrot Coal, and

Anthraconaia pulchella is found in the upper band, above the Twenty Inch Coal. Four marine bands have been found so far. The Queenslie Marine Band at the bottom of the group is represented by a thin bed of mudstone containing *Lingula mytilloides* and foraminifera. In the Lower *A. similis–A. pulchra* Zone the Bankhead and Eastside marine bands contain *Lingula* and the trace-fossil *Planolites ophthalmoides*. Skipsey's Marine Band at the top of the group is distinctive in its lithology of black, carbonaceous, calcareous siltstone. Although it is only a thin bed it carries a varied fauna of brachiopods, bivalves, foraminifera and conodonts.

Just over 300 m of Upper Coal Measures are present. Much of the sequence has been subjected to secondary reddening by oxidation but in the lower beds cyclic sequences similar to those of the Middle Coal Measures can be recognized. The upper beds are predominantly red sandstone with subordinate bands of purple mudstone and siltstone. The strata are poorly fossiliferous with only a few bands containing *Spirorbis*, *Anthraconauta*, *Naiadites* and *Euestheria*. The occurrence of *Anthraconauta phillipsii* suggests that the *A. phillipsii* Zone is represented and the presence of the Lagrae Marine Band in lower strata indicates that the Upper *A. similis–A. pulchra* Zone is also represented, although none of its diagnostic mussel fauna has been found.

Thornhill

An outlier of Carboniferous strata, only slightly larger than that of Sanquhar, occupies the valley of the River Nith a few kilometres downstream around the village of Thornhill. The Carboniferous beds crop out in a fringe around outcrops of basaltic lava and sandstones of New Red Sandstone age. Much of the boundary of the outlier is the outcrop of the unconformity between the Carboniferous and underlying Ordovician and Silurian strata, and the Carboniferous is in turn overlain unconformably by the New Red Sandstone strata. Most of the Carboniferous outcrop is of beds of Coal Measures age but older strata occur in narrow outcrops along parts of the western and southern margins of the outlier.

Little is known in detail about the outlier because there has been no mining of coal and only a few exploratory boreholes have been sunk. From surface observations the structure can be seen to be an elongate basin with a north–south axis lying towards the eastern side of the outlier. The more important faults appear to have a northerly orientation.

At the northern end of the outlier the Carboniferous Limestone Series is represented by some 15 m of mottled grey and purple sandstones, siltstones and mudstones best seen in the Enterkine Burn. Two marine bands have been recorded. The upper contains only a poor fauna but the lower yields a rich assemblage of brachiopods and bivalves similar to those found near Sanquhar. In the southern part of the outlier about 45 m of strata have been recorded. The beds are similar in lithology and include at least four marine bands, two of which are limestones of sufficient thickness to have been worked in several quarries. One of these is a red dolomite at least 3·5 m thick which has been quarried and mined at Barjarg. Some of the bands contain a fairly rich fauna of brachiopods and bivalves together with a few corals. These assemblages suggest comparison with those from similar strata in areas to the south of Thornhill. All the Carboniferous Limestone Series of Thornhill is thought to be of upper Viséan age.

The Millstone Grit Series consists of about 20 m of mainly white sandstones with beds of mottled shale and seatclay. Some of the sandstones are coarse-grained and pebbly and their bases clearly mark planes of erosion, suggesting that the beds were accumulated during intermittent periods of deposition. One or two beds of bauxitic clay have been reported as up to 2·5 m in thickness. Poor faunas of brachiopods and bivalves have been found in two thin marine bands which may represent the Polhote and Tait's marine bands of Sanquhar. In places the whole sequence passes laterally into sandstones which are indistinguishable from those of the overlying Coal Measures. The base of the Coal Measures is therefore difficult to establish although there may be a substantial break in sequence, since the poor faunas suggest that the strata of the Millstone Grit Series represent only the lower part of the Namurian.

The Coal Measures (Fig. 15) are about 150 m thick. They are mainly grey, red and purple in colour and consist of cyclic developments of sandstone, siltstone, mudstone and seatclay. Coals which may have been in the sequence originally appear to have been removed by oxidation which also gave rise to the secondary reddening of the associated strata. Non-marine bivalves or mussels are commonly present in the roof-beds of the coal-positions. The sequence has been divided at the base of the Queenslie Marine Band into Lower and Middle Coal Measures. The topmost strata may include a thin development of Upper Coal Measures but the presence of Skipsey's Marine Band, normally at their base, has not been definitely established.

The Lower Coal Measures are 73 m in thickness. The lowest beds are coarse-grained sandstones which locally form a prominent topographic feature. In the overlying cyclic deposits four coal-positions have been recognized and mussels occur at several horizons. The *C. communis* Zone is well represented in the lower bands and at least one band near the top contains an assemblage typical of the lower part of the *A. modiolaris* Zone.

The Middle Coal Measures show a cyclic development throughout their 76 m. Except for their red colour and the lack of coal they are very similar to Middle Coal Measures strata in other areas. Several coal-positions have been recorded and mussels are found in the overlying beds of mudstone. Although the faunas are poor they clearly represent both the upper part of the *A. modiolaris* Zone and the Lower *A. similis–A. pulchra* Zone. The sequence contains three marine bands including the Queenslie Marine Band at the base. It has been recognized in only one borehole where the fauna comprised *Lingula mytilloides* with specimens of *Lioestheria vinti* in closely associated strata. Of the two younger marine bands, the lower has yielded only *Lingula* while the upper contains in addition several forms of foraminifera and the trace-fossil *Planolites ophthalmoides.*

Solway Firth

Five small areas of Carboniferous outcrop are well exposed on the shore of the Solway Firth between Kirkcudbright and Dumfries. In each of these outcrops only beds of the Carboniferous Limestone Series are known to be present. The Carboniferous strata are faulted against the Silurian rocks of the Southern Uplands to the north but there are also several good sections showing the unconformable relationship of the Carboniferous to the underlying Silurian strata.

The most westerly outcrop extends along the Rerrick shore for 12 km from White Port to Door of the Heugh. The sequence includes some 750 m of strata which consist mostly of pink, red and brown sandstones and conglomerates with subordinate bands of shale and mudstone and a few thin limestones. The following succession has been established:

	metres
Rascarrel Sandstones and Conglomerates	400
Barlocco Conglomerate . . . . . over	60
Orroland Limestone Beds	25
Wall Hill Sandstones	275

Apart from plants fossils are restricted to the Orroland Limestone Beds in which a poor marine fauna, including specimens of *Antiquatonia teres* and *Syringothyris cuspidata*, has been recorded.

Farther east on the Colvend shore three small patches of Carboniferous strata are exposed. From Castlehill Point to Gutcher's Isle the beds total less than 30 m and consist mainly of a basal breccia overlain by sandstones and conglomerates in which two fossiliferous bands have yielded a fauna comprising mostly brachiopods and bivalves. At Portowarren the succession is just over 45 m of sandstones and conglomerates with thin beds of shale and sandy limestone. Algal fragments have been recorded together with a poorly preserved marine fauna in which nautiloids are the most abundant forms. The smallest outcrop is at Southwick Merse where only patches of conglomerate are seen.

In the Kirkbean outcrop due south of Dumfries Carboniferous strata are at the surface over an area of about 25 square kilometres and are best seen on the shore from Southerness to Carsethorn. The strata are folded into anticlines and synclines most of which plunge towards the north-east. Numerous faults are orientated in a west-north-westerly direction. About 750 m of beds are present and they are classified locally as follows (Fig. 14):

	metres
Arbigland Group . . . . . at least	300
Thirlstane Sandstone	25
Powillimount Beds	135
Gillfoot Beds	120–180
Southerness Beds	135
Basal Cementstones . . . . . possibly hundreds of metres	
Basaltic lavas	15

The basaltic lavas are not exposed in the shore section but there are several outcrops in Kirkbean Glen. Some doubt has been expressed as to their age but they are thought to represent the Birrenswark Lavas which in other areas are taken to be of Carboniferous age. The Basal Cementstones are poorly exposed and their relationship to the underlying strata is obscure. They consist of thinly bedded mudstones, shales, siltstones and sandstones with thin bands and lenses of fine-grained limestone or cementstone. The few fossiliferous beds yield poorly-preserved molluscs. The Southerness Beds consist of thinly bedded limestones, sandy limestones, calcareous shales and flaggy sandstones. Some beds are highly fossiliferous with a faunal assemblage mainly of brachiopods and molluscs. Prominent algae have been recorded at two horizons. In one limestone specimens of *Antiquatonia teres* and *Syringothyris*

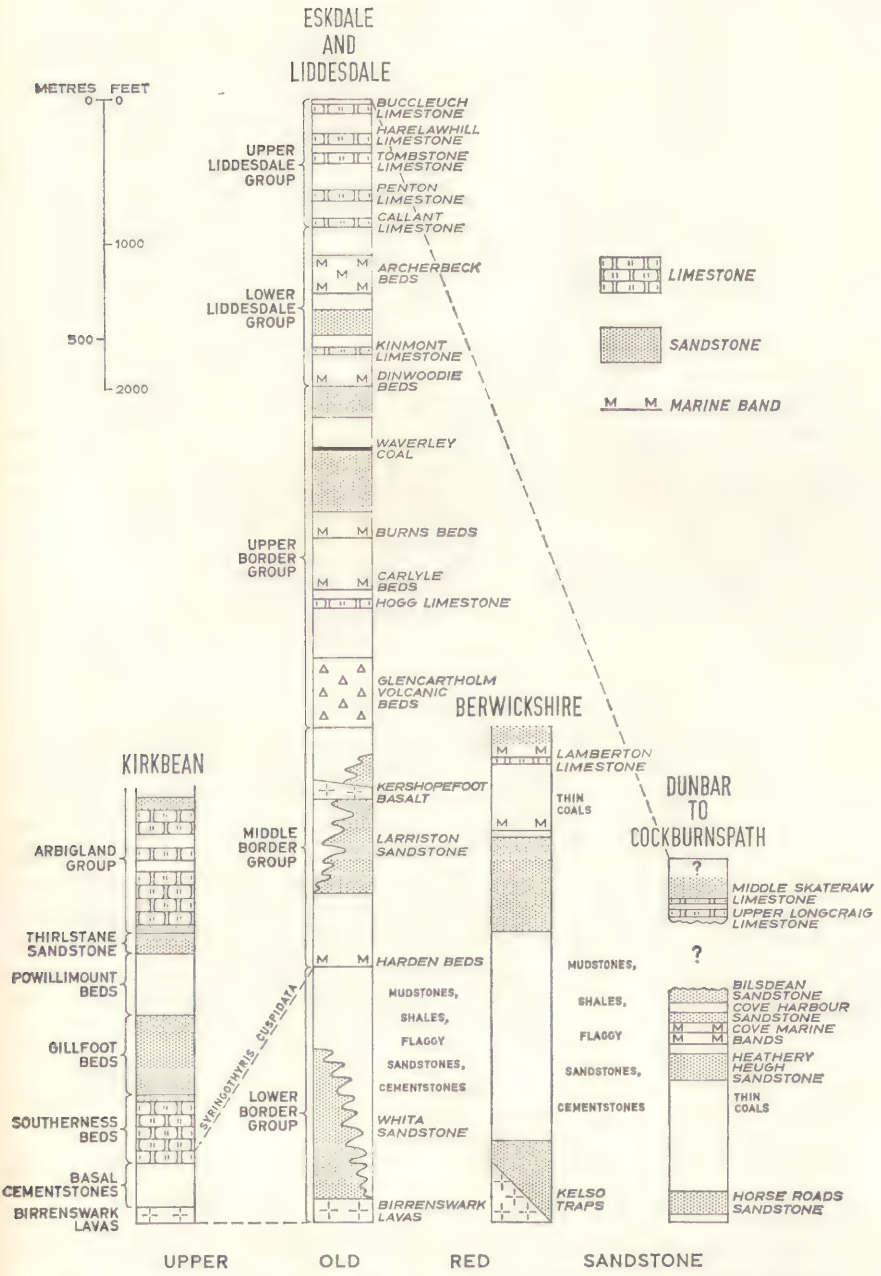


FIG. 14. *Comparative vertical sections of the Carboniferous Limestone Series*

cuspidata are closely associated, suggesting that the strata may approximate in age to the Orroland Limestone Beds farther west and the Harden Beds to the east. The dominant lithologies of the Gillfoot Beds are reddish brown sandstones, conglomerates and breccias. Subsidiary beds of shale, calcareous

sandstone and limestone occur and some of these yield a poor marine fauna comprising mainly brachiopods and bivalves together with a few specimens of the coral *Lithostrotion*. Although they consist mainly of sandstones and shales the Powillimount Beds are notable for the oolitic nature of some of their limestones together with the associated prominent development of algae. They pass up abruptly into the Thirlstane Sandstone which is pink and red, mostly medium-grained and prominently current-bedded. This sandstone is faulted against the highest beds in the local sequence, the Arbigland Group, and the throw of the fault is unknown. In the Arbigland Group the lowest beds are sandstones, in places calcareous and argillaceous, with thin bands of gritty and oolitic limestones containing algal debris. They pass up into massive coarse-grained carbonaceous and calcareous sandstones interbedded with limestones and shales which yield an abundant marine fauna. The assemblages include corals, brachiopods, bryozoa and molluscs and are notable for the abundance and fine preservation of compound corals. These topmost strata are clearly of Viséan age and may be somewhat later in the Carboniferous sequence than any of the other strata present along the shore of the Solway Firth.

Solway Firth to Cheviot Hills

This most extensive of Carboniferous outcrops extends over about 470 square kilometres for a distance of some 75 km along the border between Scotland and England from Cummertrees on the Solway Firth by way of Ecclefechan, Langholm, Canonbie and Newcastleton to the Cheviot Hills. It contains the thickest development, totalling some 3500 m, and most complete sequence of Carboniferous strata in the south of Scotland. The outcrop is the northern fringe of the great area of Carboniferous outcrop in the north of England. In most places along its northern margin the strata rest conformably on beds which have been referred to the Upper Old Red Sandstone, but here and there the Carboniferous appears to overlap on to the Silurian. The Carboniferous in turn is overlain unconformably by New Red Sandstone, which oversteps westwards from the youngest Carboniferous beds near Canonbie on to strata low in the Carboniferous sequence in the Eaglesfield area. Coals in the sequence gave rise to the now abandoned mining industry near Canonbie and

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PLATE VII

LOWER CARBONIFEROUS FOSSILS

1. *Sphenopteris affinis* Lindley and Hutton
2. *Woodocrinus liddesdalensis* Wright
3. *Edmondia sulcata* (Fleming)
4. *Polidevcia attenuata* (Fleming)
5. *Nuculopsis gibbosa* (Fleming)
6. *Composita* cf. *ambigua* (J. Sowerby)
7. *Eomarginifera setosa* (Phillips)
8. *Lithostrotion junceum* (Fleming)
9. *Limipecten dissimilis* (Fleming)
10. *Spirifer trigonalis* (Martin)
11. *Productus concinnus* (J. Sowerby)
12. *Syringothyris* cf. *cuspidata* (J. Sowerby)

All figures approximately natural size.

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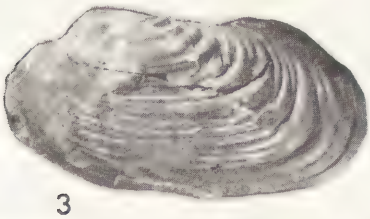

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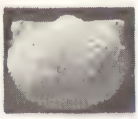

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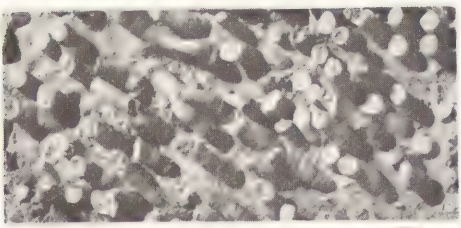

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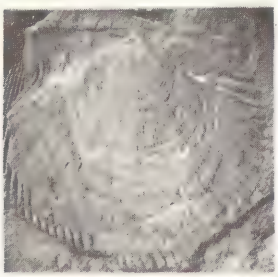

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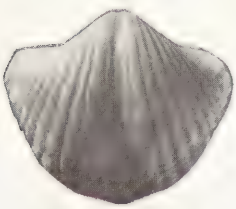

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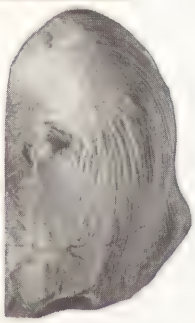

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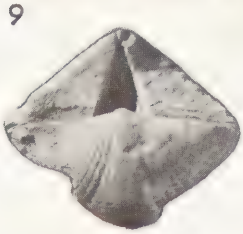

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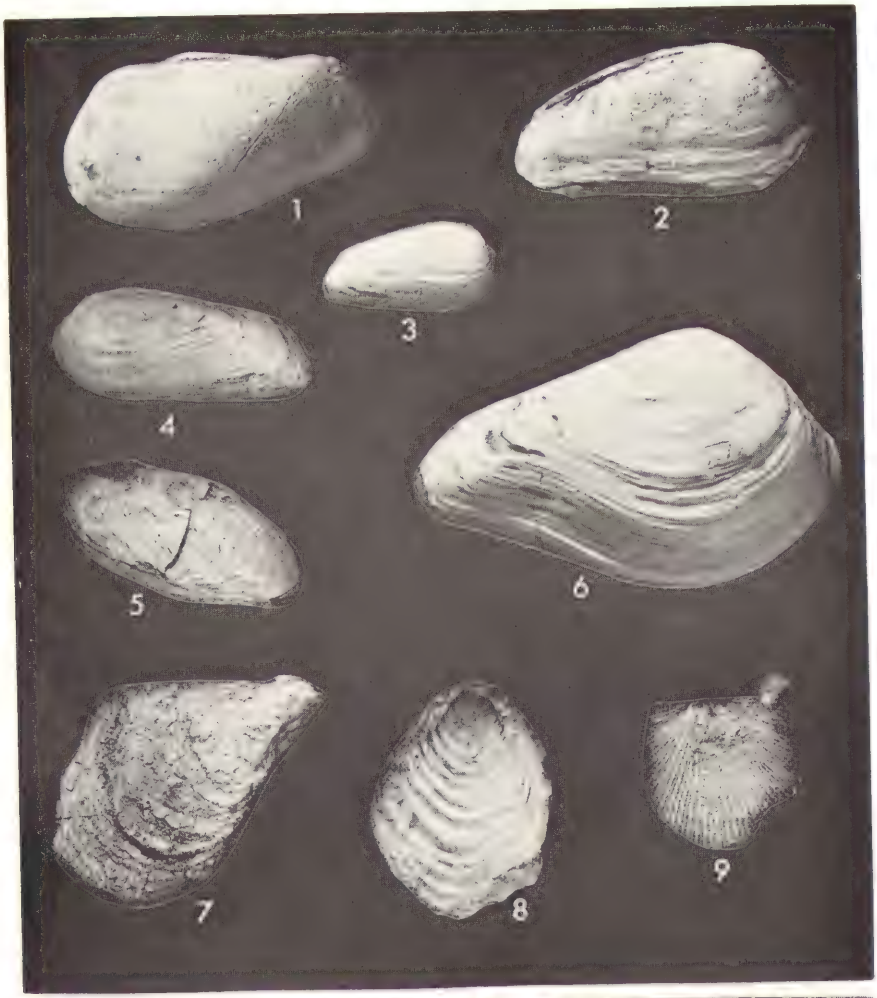
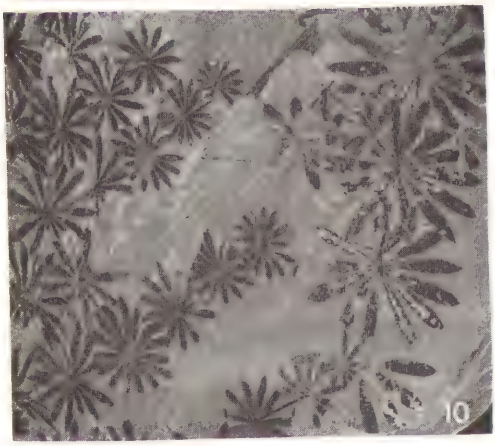
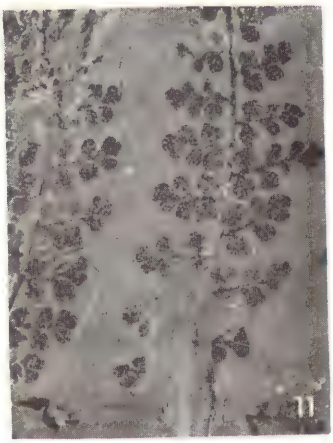
PLATE VIII







some of the limestones are of sufficient thickness and quality to be worked at present.

Although complex in detail the general structure is simple. The regional strike is north-easterly, the strata dipping gently to the south-east. Folding is mainly over axes trending north–south. The beds have been disrupted by numerous north-easterly faults with downthrow predominantly to the south-east. There has been little intrusive igneous activity apart from the emplacement of numerous small volcanic necks which now protrude above the Carboniferous strata to form prominent topographic features.

The lowest 2000 m of the sequence constitutes the Carboniferous Limestone Series (Fig. 14) which has been locally divided as follows:

	metres
Upper Liddesdale Group	275
Lower Liddesdale Group	275
Upper Border Group	675
Middle Border Group	425
Lower Border Group	450

The base of the Lower Border Group coincides with the base of the Carboniferous at the bottom of the Birrenswark Lavas. Several flows of basaltic lava can be differentiated in the total thickness of up to 90 m. In places their outcrop forms a low range of hills with north-facing escarpments. The bulk of the group is composed of sediments which vary markedly in lithology from west to east. In the west they are arenaceous in the lower part, including the Whita Sandstone of Langholm, and pass up into thinly bedded mudstones, siltstones and sandy cementstones or limestones with very few fossils. Farther east, however, the beds are alternating mudstones and limestones crowded with *Serpula*, the bivalve *Modiolus latus* and ostracods, and including numerous prominent algal bands. Marine faunas occur near the top of the group, locally at the base of the Harden Beds, but for lack of diagnostic assemblages the age of all the strata is in doubt. They are certainly not younger than early Viséan but Tournaisian may be represented.

The Harden Beds and associated strata at the bottom of the Middle Border Group yield abundant specimens of *Syringothyris cuspidata* which invites comparison with similar faunas in the Southerness Beds and Orroland Limestone Beds of the outcrops west of Dumfries. The group locally includes

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PLATE VIII

UPPER CARBONIFEROUS FOSSILS

1. *Anthraconaia robertsoni* (Brown). Middle Coal Measures.
2. *Anthracosia* cf. *aquilina* (J. de C. Sowerby). Middle Coal Measures.
3. *A. ovum* Trueman and Weir. Middle Coal Measures.
4. *A. disjuncta* Trueman and Weir. Middle Coal Measures.
5. *Anthraconauta phillipsii* (Williamson). Upper Coal Measures.
6. *Carbonicola pseudorobusta* Trueman. Lower Coal Measures.
7. *Naiadites quadratus* (J. de C. Sowerby). Middle Coal Measures.
8. *Posidonia sulcata* (Hind). Skipsey's Marine Band, Middle Coal Measures.
9. *Dunbarella macgregori* (Currie). Skipsey's Marine Band.
10. *Annularia radiata* Brongniart. Lower Coal Measures.
11. *Sphenopteris nummularia* Gutbier. Middle Coal Measures.

All figures approximately natural size.

all the strata up to the base of the Glencartholm Volcanic Beds. From mudstones and limestones with marine faunas and algal bands the strata pass up through thinly bedded siltstones, sandstones and cementstones to a massive sandstone, locally called the Larriston Sandstone, which attains a thickness of 300 m in places. There is evidence of volcanic activity towards the end of the period to the east of Langholm where the 30-metre Kershopefoot Basalt caps several prominent topographical features. In the lower part of the group fossils are abundant and similar to those at the top of the Lower Border Group, but the upper part of the group is only sparsely fossiliferous. Diagnostic assemblages have not been found but the beds are considered to be lower Viséan in age.

The period during which the beds of the Upper Border Group were deposited began with a volcanic episode during which basaltic lavas, tuffs and tuffaceous sediments were laid down over at least part of the area. The rocks are known as the Glencartholm Volcanic Beds from their type-locality on the River Esk and are calculated to be about 150 m thick. They contain a poor marine fauna but are locally notable for the unusual fish and arthropod assemblages they have yielded at Glencartholm. The greater part of the group is composed of sediments. In the lower part they are predominantly marine shales, mudstones and limestones with subordinate sandstones and few thin coals and seatclays. Many of the beds are abundantly fossiliferous with rich and varied marine faunas of corals, brachiopods and molluscs. At outcrop the beds are notable for their extensive colonies of *Lithostrotion* and numerous layers of large brachiopods. In the upper part of the group the strata below the Dinwoodie Beds are predominantly arenaceous with several coals and seatclays and only a few thin marine limestones and shales. Some aspects of the fauna of the group are of interest. Several forms of *Lithostrotion* appear for the first time in the sequence and the trepostomatous bryozoa *Dyscritella nana* and *Stenodiscus* together with the bivalves *Prothyris breviformis*, *P. oblonga*, *Pteronites angustatus* and *Modiolus oblongus* seem to be confined to this group of strata. In terms of the coral-brachiopod zones the strata range in age from C_2S_1 to S_2 but the boundary between the zones is obscure.

The lower half of the Lower Liddesdale Group consists of fine- to medium-grained sandstones with subsidiary beds of marine shale and limestone and a few thin coals and seatclays. At the bottom of the sequence the Dinwoodie Beds, some 30 m of marine shales, are notable for their rich and varied bryozoa content and because the fauna contains several forms, including *Lithostrotion junceum* and *Gigantoproductus latissimus*, which have not been recorded from older strata. The upper part of the group is composed almost entirely of highly fossiliferous marine shales and limestones, collectively called the Archerbeck Beds. The fauna, which is the most abundant in the whole Carboniferous sequence, is composed mainly of bryozoa, corals, brachiopods and bivalves. It is noteworthy that *Eomarginifera*, *Gigantoproductus giganteus*, *Pernopecten sowerbii* and *Beyrichoceratoides redesdalensis* appear in these beds for the first time in the sequence. The coral-brachiopod assemblages suggest that there is some evidence for taking the base of D_1 at the base of the group.

In the Upper Liddesdale Group, which extends from the base of the Callant Limestone up to the top of the Carboniferous Limestone Series at the base of the Catsbit Limestone, the strata are all of Yoredale type facies. They have

been deposited in regular rhythmic units, each unit generally consisting of sandstone, siltstone, mudstone, limestone, coal and seatearth in descending order. Some 120 m of the beds are particularly well exposed in the fine section at Penton Linns on the Liddel Water. The lime content of some of the limestones is high and several have been worked from time to time. Mining at Harelawhill near Canonbie is in the Harelawhill Limestone which is used mainly for agricultural purposes (Plate XA). The beds have long been famous for their fossils. The limestones contain mainly corals and brachiopods while most of the forms in the shales are brachiopods and molluscs. Of the corals *Aulophyllum*, *Dibunophyllum* and *Lithostrotion* are prominent and Gigantoproductids of both latissimoid and giganteid form together with *Eomarginifera* are of common occurrence. The bivalve *Posidonia becheri*, generally indicative of the goniatite 'zone' P_1, is relatively abundant in the lower part of the group and is of common occurrence in the shales between the Tombstone and Gastropod limestones at Penton Linns. The coral-brachiopod assemblages suggest a D_2 age for most of the strata but this conflicts with a D_1 age suggested by the foraminifera from the same beds.

The Carboniferous Limestone Series passes up into the Millstone Grit Series, the boundary being taken locally at the base of the Catsbit Limestone. The strata of the Millstone Grit Series, which are thought to be about 425 m thick, are not well known because they are restricted in outcrop to small areas near Canonbie where the degree of exposure is poor. Some information from old boreholes is difficult to interpret and correlation of the beds in the upper part of the sequence can only be conjectural. The rhythmic Yoredale type facies of the Upper Liddesdale Group continues upwards in the youngest beds of the Millstone Grit Series which include the Catsbit Limestone, the thickest limestone in the Carboniferous sequence. These beds contain abundant marine faunas similar to those of the underlying strata. The Yoredale type facies passes up into a sequence of sandstones with numerous rooty seatearths and thin coals, including seams collectively called the Penton Coals which have been worked locally. Throughout these beds there are several thin bands of shale mostly with *Lingula*, and only a few thin limestones and calcareous shales with more abundant and varied marine faunas. The topmost strata of the series are dominantly arenaceous with numerous rooty beds and thin coals. Some of them display secondary reddening, which may be attributed to oxidation below a land surface which subsequently subsided as younger Coal Measures strata were deposited unconformably. That most of the Millstone Grit Series is of Namurian age there is little doubt. Likewise, although there is no goniatite evidence, it is certain, from the evidence of other fossils and correlation with other areas, that beds of E_1 and E_2 age are present in the lower part of the sequence. The age of the strata towards the top of the sequence has not as yet been established.

The Coal Measures at the top of the Carboniferous sequence are over 900 m thick (Fig. 15). They rest unconformably on the Millstone Grit Series and are succeeded unconformably by the New Red Sandstone. They crop out only in a small area around Canonbie where they are poorly exposed. Details of the sequence are well known, however, from a number of boreholes which have been put down searching for coal. The sequence is divided as follows:

		metres
Upper Coal Measures	up to	800
Middle Coal Measures		180
Lower Coal Measures		30

The boundary between the lower two groups is taken at the base of the Queenslie Marine Band, the local name for the extensive marine band which is taken nationally as the boundary between these groups. In common with Scottish practice the boundary between the Middle and Upper Coal Measures is at the top of the local Skelton Marine Band, which is thought to be equivalent to the well-known Skipsey's Marine Band of the Midland Valley. In England and Wales the boundary between these two groups is taken somewhat higher in the succession.

Only the upper part of the Lower Coal Measures has been recognized in the area. The strata consist of sandstone with large ragged and angular fragments of siltstone which passes up into siltstones with thin bands of sandstone and seatearth and two thin coal seams. The only mussel band recorded has yielded representatives of the *Anthracosia regularis* fauna which is commonly found in the lower part of the *A. modiolaris* Zone.

In the Middle Coal Measures a typical lithological sequence in descending order is: coal, rooty seatearth, sandstone, siltstone, mudstone with shells, carbonaceous shale with plant and fish remains. The whole succession is made up of these cyclic sequences which vary in thickness from 3 to 30 m. The numerous coals range up to 3 m in thickness and are highly volatile with strong caking properties. The thicker seams have been worked out near outcrop but remain untouched where they lie at greater depths. In places some of the topmost beds have been partially reddened by secondary oxidation of their iron content. There are few mussel bands in the sequence. Nevertheless it has been established that the assemblages fall into the upper part of the *A. modiolaris* Zone and the Lower *A. similis–A. pulchra* Zone. The boundary between the two zones is taken arbitrarily at the Nine Foot Coal. The four marine bands in the succession are characteristically varied in development. The Queenslie Marine Band at the bottom yields only *Lingula* and fish remains but the associated non-marine bivalve assemblages show that it can be correlated with certainty with the Clay Cross Marine Band of the Pennines. In the Lower *A. similis–A. pulchra* Zone the Sandwich Marine Band contains foraminifera, *Lingula* and *Orbiculoidea*, the Knottyholm Marine Band yields *Lingula*, *Orbiculoidea* and the trace-fossil *Planolites ophthalmoides* and at the top the Skelton Marine Band contains all these fossils together with conodonts. These bands are correlated with the Haughton, Sutton and Mansfield marine bands of the Pennines respectively.

Practically all the beds of the Upper Coal Measures have been reddened by secondary oxidation. In places the chemical reactions involved have been so extreme that the original sedimentary structures can no longer be recognized. As a result, although there is little change in the sandstones except in colour, the different types of argillaceous sediment are, for the most part, indistinguishable. Much of the upper part of the sequence, therefore, consists of alternations of pink sandstones and red and purple massive silty mudstones. No coal has been recorded amongst these beds. In the lower part of the group normal coal seams are found amongst grey beds interbedded with reddened beds amongst which the coals have been oxidised and, in places, replaced to

some extent by dolomitic limestone. All that remains in the coal position is a thin band of irony rubble or streaky limestone. Throughout the sequence there are a few thin beds of freshwater limestone with abundant *Spirorbis* and ostracods. Three marine bands are known. The lowest, the Viaduct Marine Band, contains foraminifera and *Lingula*, and above it the Rowanburnfoot Marine Band yields a similar fauna together with intercalations containing abundant specimens of *Lioestheria*. The Riddings Marine Band, the youngest band of its kind in the Carboniferous sequence, contains foraminifera, *Lingula*, *Orbiculoidea* and conodonts. These bands correlate with the *Edmondia*, Shafton and Top marine bands of the Pennines respectively. Few mussels are present and only the *A. tenuis* Zone has been proved conclusively. By implication, however, some of the strata fall into the Upper *A. similis–A. pulchra* and *A. phillipsii* zones.

Berwickshire

Carboniferous rocks crop out over an area of at least 300 square kilometres of Berwickshire. The principal outcrop extends westwards from the Border to Duns and Greenlaw and southwards beyond Kelso. A further small area occupies a narrow strip along the coast southwards from Burnmouth. Except on the coast the degree of exposure is poor and over much of the outcrop little is known in detail of sequence or structure of the strata. All the beds are considered to be of Lower Carboniferous age and are included in the Carboniferous Limestone Series (Fig. 14).

Around Kelso, where the rocks are disposed in a gentle syncline with a north-easterly axis, the oldest strata to be included in the Carboniferous are the Kelso Traps. They reach the surface in a U-shaped outcrop from Duns southwards to Greenlaw and thence across the River Tweed to the north flank of the Cheviot Hills. At least six flows of basaltic lava have been distinguished in their total thickness of 120 m which includes several beds of basaltic tuff. There is apparent thinning northwards and no igneous rocks have been found in the sequence to the north and east of Duns, where sediments of Carboniferous age rest directly on strata of Upper Old Red Sandstone facies. The sediments consist of mudstones and shales with bands of cementstone and flaggy sandstones together with bodies of cross-bedded channel sandstone up to 30 m thick. Some of the fine-grained beds are brightly coloured and sun-cracks, rain-pits and thin bands of gypsum are characteristic features. The sequence is best seen on the shore at Burnmouth where some 500 m of strata are exposed. There the lowest 45 m or so of reddish sandstone, including calcareous bands resembling cornstones, are of Upper Old Red Sandstone facies. In the Kelso and Greenlaw districts the beds succeeding the Kelso Traps include concretionary cornstones. The lowest of these beds are tuffaceous, gritty and locally pebbly. They include the Carham Stone, a cherty magnesian limestone up to 7·5 m thick, which is thought to have been accumulated by chemical precipitation from waters enriched in lime by showers of volcanic dust towards the end of the main period of volcanic action. The strata as a whole are not abundantly fossiliferous but several bands contain mainly plants, the bivalve *Modiolus*, ostracods and fish, none of which indicate the age of the beds in detail.

Strata higher in the sequence have been recognized only on the coast south of Burnmouth. Some 200 m of sandstone which crop out on the shore for

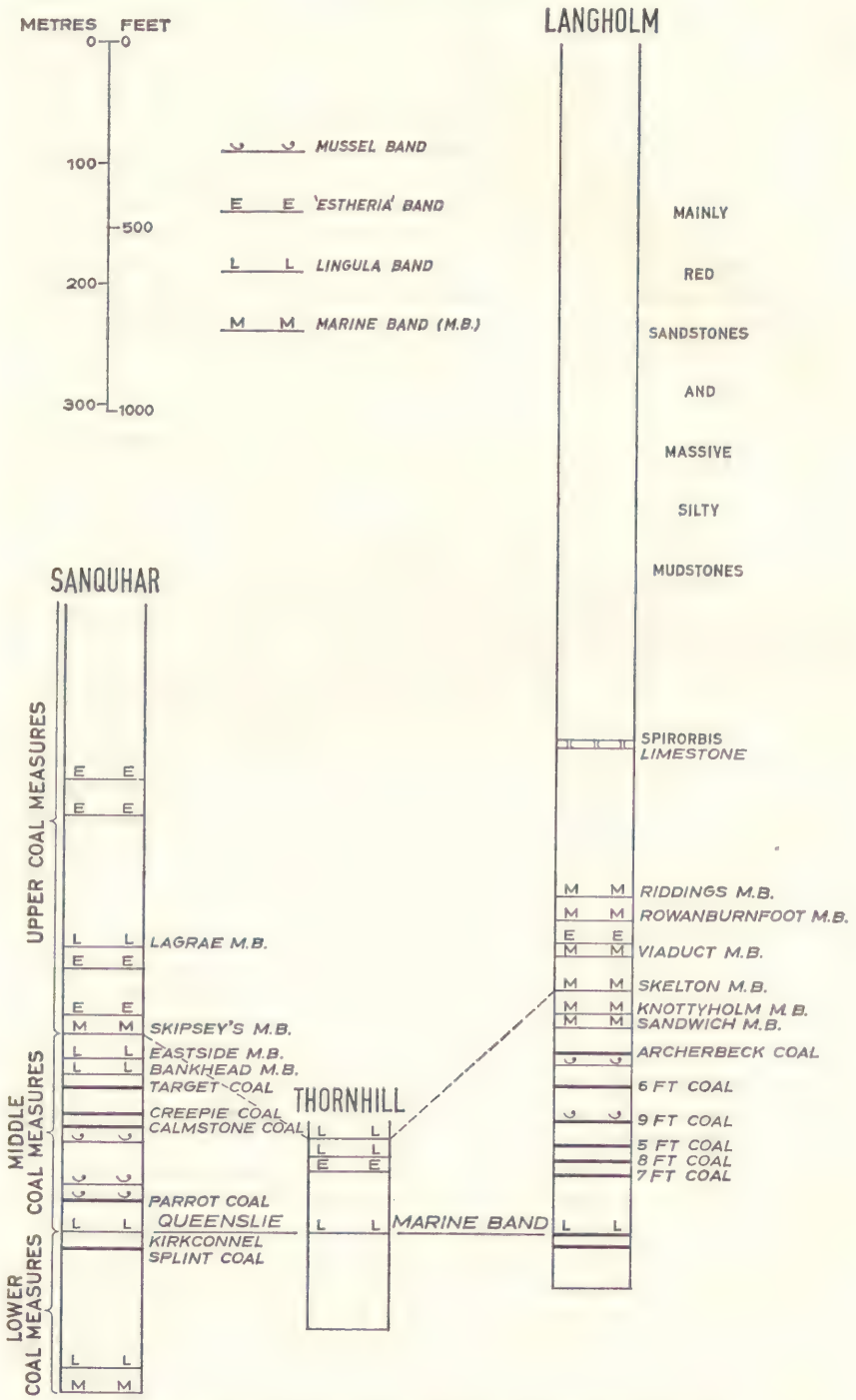

FIG. 15. *Comparative vertical sections of the Coal Measures*

nearly 2 km south from Burnmouth has been correlated with the Fell Sandstone of Northumberland. It is white, yellow and pink, and mostly false-bedded. The bedding is locally convolute and the lithology is diversified in places by bands of quartz pebbles, lenses of red sandy mudstone and ironstone nodules. On the cliffs to the south the sandstones are overlain by about 75 m of alternating mudstones, sandstones and seatearths with a few thin coals and cementstone bands. Coal from this part of the sequence was worked at Lamberton in the 19th century. Apart from fairly abundant plant remains the beds are poorly fossiliferous with only a few bands containing *Lingula*, bivalves and ostracods. Near the top of the sequence a few beds contain a marine fauna including crinoids and brachiopods. The youngest strata exposed at Hilton Bay and Lamberton include the Lamberton Limestone, which has been taken as the equivalent of the Dun Limestone at the base of the Lower Limestone Group of Northumberland. It is up to 1·5 m thick and yields a marine fauna including *Lithostrotion*, Gigantoproductids and *Punctospirifer*. It passes up into 7·5 m of marine shales closely overlain by a red sandstone with an irregular base which is up to 45 m thick just south of the Border.

South-east of Dunbar

From Pease Bay, near Cockburnspath, to within 2 km of Dunbar an upward sequence of Lower Carboniferous rocks is well exposed on the shore. The area occupied by the outcrop extends for about 3 km inland where the strata are faulted against rocks of Upper Old Red Sandstone age. The beds fall into the Calciferous Sandstone Measures and the Lower Limestone Group of the Midland Valley classification, the boundary being taken at the base of the marine beds associated with the Upper Longcraig Limestone (Fig. 14).

More than 300 m of the strata at the bottom of the Calciferous Sandstone Measures can be seen on the shore in the neighbourhood of Pease Bay and Cove. The sequence is broken only by the Cove Fault which has cut out some 150 m of beds. The arbitrary base of the Carboniferous is taken just above a prominent deep red sandstone with creamy chert lenses. The oldest beds are shales and cementstones with plant fragments. They are succeeded by the Eastern Hole Conglomerate, a distinctive 1-metre cementstone breccia, overlain by a band of cementstone yielding *Sanguinolites*. The Horse Roads Sandstone, 45 m thick, is false-bedded and near the top contains large calcareous concretions. It passes up into a series of shales with impersistent cementstones. The relationship of these beds to the Kip Carle Sandstone is obscure because the latter, a pale brown medium- to coarse-grained sandstone, is associated with the Cove Fault, the outcrop of which has not been defined with certainty. The beds beyond the fault and higher in the sequence are shales with thin coals and ironstone ribs. They are succeeded by the Heathery Heugh Sandstone, a mainly red and purple rock which forms a prominent bluff and stack at Hollow Rock. Some 12 m above it a bed of shale yields specimens of *Cardiopteris polymorpha*. The Cove Lower Marine Band is well exposed next to the southern part of the Cove Harbour sea wall and also at several localities in the Thornton Burn. It consists of up to 5·5 m of calcareous sandstone and sandy shale and yields an assemblage of brachiopods, gastropods and bivalves characterized by the abundance of *Productus redesdalensis* and the occurrence of the goniatite *Beyrichocera-*

toides redesdalensis. The Cove Upper Marine Band crops out at the north end of the sea wall and also north-westwards along the coast at Linkhead where it is known as the Linkhead Limestone. Up to 2·5 m of calcareous sandstone and siltstone contain brachiopods and bivalves including *Spirifer duplicicosta* and *Gigantoproductus*. The Cove Harbour Sandstone, a red false-bedded rock, forms a prominent bluff north of the harbour and shortly above it in the sequence is the Cove Oil-shale, a distinctive rock weathering bright red at the top and containing abundant pyritized plant fragments.

The highest beds of the Calciferous Sandstone Measures crop out on the shore northwards from Thorntonloch to Long Craig. The dominant lithology is sandstone but two marine limestones and shales, the Lower and Middle Longcraig limestones, occur towards the top of the sequence. The Middle Longcraig Limestone is a particularly striking white nodular rock with a fauna including solitary corals, abundant specimens of the brachiopod *Composita*, and a Rhynchonelloid. The Limestone is characterized by large colonies of species of *Lithostrotion*.

Inland exposures are few and of limited extent. At the south-western end of the outcrop, however, near Oldhamstocks 60 to 90 m of basaltic lavas and tuffs can be seen amongst sediments which are mainly sandstone. These beds are taken to be Carboniferous in age but their precise position in the sequence is unknown.

Over 60 m of Lower Limestone Group strata are disposed in a broad syncline extending from Barns Ness Lighthouse to Catcraig on the coast and inland for almost 3 km. Some of the beds are repeated in a smaller fold cropping out along the coast towards Dunbar. In the main the sequence is a cyclic development of sandstones and marine limestones and shales. Many of the strata are fossiliferous and in some beds marine shells are abundant. At the bottom of the succession the Upper Longcraig Limestone is about 5·5 m thick. It is cream-coloured and crowded with a rich marine fauna of corals and brachiopods, particularly in the upper part. Some 6 m higher in the sequence the Lower Skateraw Limestone, up to 0·6 m thick, is distinguished by a band of Gigantoproductids at the base. The beds above it are mainly mudstone and seatclay with a thin coal underlying the Middle Skateraw Limestone. It is up to 5·5 m thick and is characterized by a band 0·3 m thick near the top containing abundant specimens of *Saccamminopsis fusulinaformis*. Above the limestone a bed of calcareous shale contains many corals, brachiopods and bivalves, and trilobite fragments are fairly common. A metre or so higher in the sequence a thin limestone, the Upper Skateraw Limestone, is associated with shales yielding rich marine faunas. Later beds

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PLATE IX

A. Anticline in rocks of the Upper Liddesdale Group, Carboniferous Limestone Series, at Penton Linns, Liddel Water, Dumfriesshire. (Geol. Surv. Photo. No. C4047).

B. Cliffs at Cove Harbour, Berwickshire. Steeply dipping rocks of the Calciferous Sandstone Measures, Carboniferous Limestone Series, including the Heathery Heugh and Cove Harbour sandstones. (Geol. Surv. Photo. No. D1151).

C. Carboniferous-Ordovician unconformity, Dumfriesshire. Rocks of the Carboniferous Limestone Series resting unconformably on steeply dipping Ordovician beds in the Loch Burn, Sanquhar. (Geol. Surv. Photo. No. C3570).

A

B

C

PLATE X

A

B

are mainly sandstone but they include three poorly developed marine horizons which are in upward sequence, the Chapel Point Limestone, the Dryburn Foot Limestone and the Barness East Limestone. All these limestones are sandy and sparsely fossiliferous on the whole, but several surfaces display striking developments of 'cauda-galli' markings. The sandstones above the Barness East Limestone are taken to represent part of the Limestone Coal Group of the Midland Valley classification.

All the strata below the Barness East Limestone are of Viséan age or older. Some of the earliest beds may be of Tournaisian age but there is as yet no direct evidence that this is so. The oldest marine bands in the sequence, the Cove Lower and Cove Upper marine bands, are correlated with the Dun and Woodend limestones of Berwick and with the Redesdale Ironstone and Redesdale Limestone of Northumberland, respectively. This being so the Cove Lower Marine Band, although it does not yield a diagnostic fauna, can be taken to be of B age related to goniatites and, therefore, mid-Viséan. The youngest beds in the sequence clearly represent the Lower Limestone Group of the Midland Valley and are therefore of P_2 age or uppermost Viséan.

PLATE X

A. Limestone mines, Harelawhill, near Canonbie, Dumfriesshire. Quarry and mines in the Harelawhill Limestone (Upper Liddesdale Group, Carboniferous Limestone Series). (Geol. Surv. Photo. No. C4054).

B. Limestone Quarry, Dunbar, East Lothian. Large-scale modern quarry in the Middle Skateraw Limestone and associated beds (Lower Limestone Group, Carboniferous Limestone Series). Dunbar Works of the Associated Portland Cement Manufacturers Limited. (Geol. Surv. Photo. No. D1142).

7. VOLCANIC ROCKS OF CARBONIFEROUS AGE

Ample evidence of widespread volcanic activity in the south and east of the Southern Uplands during Carboniferous times is seen in the extensive outcrops of lavas together with the abundance of volcanic necks and intrusions of various forms (Fig. 13). The most common rock is olivine-basalt and for convenience the main characteristics of the principal types are summarized briefly below:

MACROPORPHYRITIC BASALTS

(Phenocrysts more than 2 mm in length)

Markle type: with abundant phenocrysts of labradorite and some of olivine.
Dunsapie type: with abundant phenocrysts of labradorite, olivine and augite.
Craiglockhart type: with abundant phenocrysts of olivine and augite.

MICROPORPHYRITIC BASALTS

(Phenocrysts less than 2 mm in length)

Jedburgh type: with abundant phenocrysts of labradorite and some of olivine.
Dalmeny type: with abundant phenocrysts of olivine and sporadic labradorite and augite.
Hillhouse type: with abundant phenocrysts of olivine and augite.

The ground mass constituents are labradorite, augite and iron ore.

At least three episodes of volcanic activity during which lavas were extruded have been recognized in the Carboniferous. The earliest and most extensive took place at the beginning of Carboniferous times when lavas in a series of interdigitating flows up to 120 m in total thickness were laid down over an area extending from the Solway Firth south of Dumfries to Duns in Berwickshire. In the west these rocks are known as the Birrenswark Lavas from the type-locality at Burnswark, a striking feature on their escarpment a short distance to the north of Ecclefechan (Plate XIA). Different types of basalt are present in the sequence but to the west of Langholm the Jedburgh type appears to be the most common and the Dalmeny type is well represented. Eastwards from Langholm, in Eskdale and Liddesdale, the predominant types appear to be Dalmeny and Dunsapie. Markle and Jedburgh types are less commonly found. The occurrence of glassy olivine-basalts, allied to Dalmeny type, and of a rare feldspathic Dunsapie type has also been noted. One of the most striking features of the Birrenswark Lavas is their alteration by deuteric activity in the consolidating lava and the effect of atmospheric weathering. Because of the advanced nature of the alteration of many of the constituent minerals it is commonly impossible to determine the type of basalt.

In Berwickshire the lavas at the base of the Carboniferous are known as the Kelso Traps. Although there is no evidence that they are absolutely contemporaneous with the Birrenswark Lavas to the west there seems to be little doubt that they were deposited at about the same time. The rocks are highly

altered olivine-basalts. A distinction has been recorded in the general disposition of the types of basalt in that the lower part of the sequence, restricted in outcrop to the area south of the Blackadder Water, consists mainly of Jedburgh and Markle types. Flows in the upper part of the sequence, which crop out in the area north of the Tweed, seem to be more basic and consist mainly of Dunsapie and Dalmeny types.

Wherever these lavas occur individual flows can be made out by the abundance of vesicles in the marginal zones associated with generally slaggy tops. In many places they are interbedded with red sandstones and shales, some of which contain a high proportion of basaltic debris. In Berwickshire some beds of basaltic tuff have been recorded but these are uncommon.

Some time later, during a second episode of volcanic activity, the Kershopefoot Basalt was deposited locally in Eskdale and Liddesdale. At outcrop the rocks cap several prominent topographic features including Windy Edge, Greena Hill, Carby Hill and Swarf Hill and they are particularly well exposed in the Kershope Burn south of Newcastleton. They are about 30 m in thickness and fairly homogeneous throughout, except near the top of the mass where the basalt is extremely vesicular and slaggy. In type the basalt varies from intermediate between Jedburgh and mugearite in the west to intermediate between Jedburgh and Markle in the east.

A short time later a further outburst of volcanic activity gave rise to the deposits known as the Glencartholm Volcanic Beds. These have been recognized at outcrop from the headwaters of the River Sark eastwards to the Liddel Water near Kershopefoot. They are about 150 m thick and consist largely of interbedded tuffs, sediments and tuffaceous sediments with varying proportions of volcanic debris. Lavas are less common and occur, up to 15 m in thickness, near the bottom of the sequence. The igneous fragments in the tuffaceous strata are mainly decomposed basaltic rocks and altered basic pumice. In places fragments of trachyte occur. The lavas are variable in type, ranging from olivine-basalts of Dunsapie and Dalmeny types to trachybasalts.

Extruded igneous rocks are also present in the Carboniferous sequence at Windburgh Hill, north-east of Newcastleton, at Catcleuch Shin on the northern shoulder of Carter Fell and at Oldhamstocks near Dunbar. Their precise age is unknown and no correlation has been made with the Kershopefoot Basalt or the Glencartholm Volcanic Beds. At Windburgh Hill and associated outcrops the strata are mainly olivine-basalts of Dunsapie and Dalmeny types overlain by beds of basaltic tuff. At Catcleuch Shin basaltic tuffs are overlain by basalts of Markle and Jedburgh type. Both tuff and basalt are present in the poorly exposed sequence at Oldhamstocks.

The vents from which these Carboniferous lavas were extruded are scattered over an area some 16 km in width extending north-eastwards from Langholm to Duns. They are mostly filled with tuff and agglomerate composed of fragments of basaltic rocks and of the country rock through which they have been blasted. Some of them are wholly or partly filled by plugs of basaltic rocks of various types. Little is known of the relative ages of individual vents. It seems unlikely that any of the Birrenswark Lavas or Kelso Traps were extruded from vents which cut strata which are clearly higher in the sequence. None of these vents cuts beds younger than the Glencartholm Volcanic Beds, however, which suggests that they were at least some of the

sources of the tuffs and basalts at that horizon and probably also of the Kershopefoot Basalt.

Of the vents which are now exposed outwith the limits of the Carboniferous outcrop, those at Arkleton Hill, Pike Fell and Cooms Fell, just to the north-east of Langholm, may mark sites from which some of the Birrenswark Lavas issued. The first two are entirely filled with plugs of basalt but at Cooms Fell the vent is mostly filled with basaltic agglomerate with only a small plug of basalt intermediate between Dalmeny and Hillhouse types. In the same district the many apparently younger vents are mostly filled with basaltic agglomerate. Some of them contain angular blocks and rounded pebbles of sediments of Upper Old Red Sandstone or Carboniferous age. The largest vent of this group is at Tinnis Hill which forms a prominent topographical feature between Langholm and Newcastleton. The vent is oval in shape and is mostly filled with fine-grained agglomerate, with a small plug of basalt intermediate between Dalmeny and Jedburgh types.

Farther to the north-east in Teviotdale a varied assemblage of vents was intruded at or about the same time. Those which form the Minto Hills and others at Troneyhill and Ancrumcraig are filled with agglomerate only. More complex vents filled with agglomerate together with basalt plugs of varied proportions form the prominent features of Rubers Law, Black Law and Lanton Hill. Dunion Hill and Fatlips Crags are examples of vents filled with plugs of basalt only.

A large number of sheets and plugs were intruded in and around the valley of the River Tweed at about the same time. Some of them may have been the sources from which the Kelso Traps were laid down but others may be associated with later volcanic activity since they appear to cut at least part of the lava sequence. Olivine-dolerite is the main rock-type in the plugs at Bemersyde, Smailholm Tower and Blinkbonny. At Mellerstain the rock is a basalt of Markle type and several different basalts have been found in the composite plug at Lurgie Craigs. Basalts of Markle, Dunsapie and Dalmeny types are common in plugs at Queenscairn, Sweethope Hill, Hareheugh Craigs, Middlethird and Knock Hill. Masses of olivine-dolerite at Wooden Hill, Rutherford, Craigover, Maxton, Brotherstone Hills and West Gordon are believed to be remnants of intrusive sheets or sills. The columnar basalt of Dalmeny type at Hexpathdean Quarry has intruded sediments of the Upper Old Red Sandstone, and similar basalts which cap Duns Law and two neighbouring hills are thought to be part of a small laccolith. Insufficient evidence has been found to establish whether the basalts of Haddenrig and Lurdenlaw or the dolerite of Peniel Heugh are sills or plugs.

Some time after this widespread intrusion and extrusion of basaltic rocks a later phase of vulcanicity gave rise to the alkaline and acid igneous rocks found in the district which probably correspond in time to the trachytic lavas and intrusions of the Garleton Hills and similar intrusions in the Campsie and Renfrewshire hills. The chief types of rock represented are porphyritic and non-porphyritic quartz-trachytes, sanidine-trachyte, sanidine-porphyry, riebeckite-bearing felsite, and basalt. The areal distribution of these rocks is similar to that of the earlier basaltic phase.

Towards the known southern limit of their occurrence they are represented by a north-easterly swarm of dykes of decomposed trachyte, quartz-trachyte and phonolitic trachyte, some feldspar-phyric, together with a few dykes of

decomposed felsite. In the same area is the intruded mass of phonolite at Pikethaw Hill, 13 km north of Langholm. Farther to the north-east similar rocks cap high ground at Skelfhill Pen, Skelfhill, Doecleugh and Penchrise. The associated vents in this district are mainly filled with agglomerate composed of fragments of grit, shale, greywacke and trachyte. The largest of these at Tudhope Hill, to the east of Mosspaul, is of special interest because it contains a large block of sandstone of Upper Old Red Sandstone age which has apparently fallen into the vent. The agglomerate is pierced by basalts of Jedburgh and Markle types at the southern end and by plugs of trachyte towards its northern end. Some 6 km to the north-east another large vent at Greatmoor Hill is filled mainly with agglomerate which is full of large bombs of olivine-basalt and blocks of grit and greywacke. The agglomerate is pierced by bodies of basalt of Dunsapie and Craiglockhart types and near its southern margin by a plug-like body of trachyte. A short distance to the east a smaller vent at Leap Hill is filled mostly by two plugs of non-porphyritic trachyte. The associated agglomerate is basaltic and is cut by a dyke-like intrusion of basalt of Dunsapie type.

Similar rocks thought to be of the same age are found commonly around Melrose in the form of laccoliths, sills, north-easterly dykes and in vents. The most spectacular occurrence is at the Eildon Hills which are regarded as representing the denuded remains of a composite laccolith (Front cover and Plate XIB). Rocks of slightly different type have been intruded sheet by sheet and now give the appearance of being stratified. Much of Eildon Wester and Eildon Mid hills is formed by riebeckite-felsite disposed in two layers. On the south-west face of the Wester Hill the upper layer shows magnificent columnar structures. The summit of Mid Hill is occupied by orthophyric riebeckite-trachyte overlying a sheet of augite-olivine-trachyte which crops out to the west. Eildon Hill North on the other hand consists of porphyritic and non-porphyritic varieties of sanidine-trachyte. Similar rocks are found as dykes and irregular elongate bodies with north-easterly orientation in the vicinity of White Law, Cauldshiels Hill and Bowden Moor to the south-west of Melrose. Sills or sheets form prominent features at Bemersyde Hill, Black Hill and White Hill to the east and north-east of Melrose.

The largest of the associated vents is the Chiefswood vent at Melrose. It is oval in shape with a north-easterly axis about 3 km long. It is filled with an agglomerate of angular fragments of Silurian and Old Red Sandstone sediments mingled with pieces of quartz-porphyry, trachyte and olivine-basalt. A small vent at Little Hill in the same vicinity is mostly filled with a plug of basaltic rock which almost certainly pierces the acid rocks of the Eildon Hills complex.

In Berwickshire four intrusions of felsite and associated rocks occur in conglomerates and sandstones of Upper Old Red Sandstone age. They form the hills of Dirrington Little Law, Dirrington Great Law, Blacksmill Hill and Kyles Hill. In the first three masses the principal constituent is a riebeckite-bearing rock similar to the felsite of Eildon Wester Hill, which suggests that they may be all part of a similar laccolith of the same age. On Kyles Hill, however, the rock is different. It consists of phenocrysts of feldspar embedded in an orthophyric groundmass of orthoclase, quartz and hematite and appears to be pierced by a dark bluish grey rock resembling andesite (see also p. 52).

At Southdean, 5 km south-east of Bonchester Bridge, a large plug is

composed of nepheline-basanite consisting of phenocrysts of olivine and pyroxene in a groundmass of pyroxene, feldspar, nepheline and iron ore. In the Midland Valley rocks of this type have been found in intrusions of late Carboniferous or, perhaps, Permian age. Further evidence of igneous intrusion in the south of Scotland in late Carboniferous times is given by a few quartz-dolerite dykes of east–west trend. One of these is well exposed as it crosses the River Esk and the Liddel Water north of Canonbie.

8. NEW RED SANDSTONE

The New Red Sandstone consists of all the rocks in the south of Scotland which have in the past been included in the Permian and Triassic systems. The twofold subdivision is retained in this account, but the boundary between the two systems is not established.

The 'Permian' system is considered to comprise all the late Palaeozoic desert-sandstones and breccias, as well as the associated lavas and intrusive rocks. This long-accepted connotation has recently been questioned on palaeobotanical grounds. Plants found near the base of the succession in central Ayrshire have been assigned alternatively to the Westphalian, to the Upper Stephanian Series at the top of the Carboniferous, or to the Autunian (basal Permian). The evidence currently available is inconclusive.

Triassic rocks occur only in an area of some 140 square kilometres between Annan and Canonbie, where they are in direct continuity with the Bunter rocks of Cumberland.

The principal '**Permian**' outcrops occupy outlying basins in the Stranraer area, in Nithsdale from Sanquhar to the Solway, and in Annandale from above Moffat to below Lochmaben. Smaller areas occur on the coast between Ballantrae and Bennane Head; in the Water of Milk, between Lockerbie and Ecclefechan; and in the Snar valley, north of Leadhills.

The Stranraer isthmus and the western shore of Loch Ryan are composed of 'Permian' sandstones and breccias which at their western boundary are seen to rest unconformably on Upper Carboniferous and Ordovician rocks, the eastern boundary, like most of the outcrop, being obscured by superficial deposits. On the Loch Ryan shore red breccias with thin beds of sandstone form cliffs up to 45 m high. The pebbles in the breccias are largely of Ordovician greywacke and chert. The outcrop, about 1·5 km wide, extends southwards to Stoneykirk, the rocks dipping gently to the east or south-east. At West Freugh, about 2·5 km north-east of Stoneykirk, a water bore proved 143 m of breccia underlain by at least 24 m of brown sandstone. The results of a recent gravity survey suggest that the rocks are mainly sandstones, which occupy an asymmetrical trough aligned north-westwards, having a maximum depth of some 900 to 1400 m in the south-eastern part of the outcrop. The eastern margin is very steep and is probably a fault.

A narrow strip of red sandstones forms the coast between Ballantrae pier and Bennane Head. At the pier they include a breccia containing pebbles of serpentinite and other rocks of the Ballantrae Igneous Complex, against which these 'Permian' rocks are everywhere faulted. In places they are cut by thin basalt dykes, probably of Tertiary age.

In Nithsdale olivine-basalt of 'Permian' age forms three small outliers, resting on Coal Measures, to the north-east and south-east of Sanquhar, and five small volcanic necks which pierce the Coal Measures nearby are taken to be of the same age. The necks are filled with angular fragments

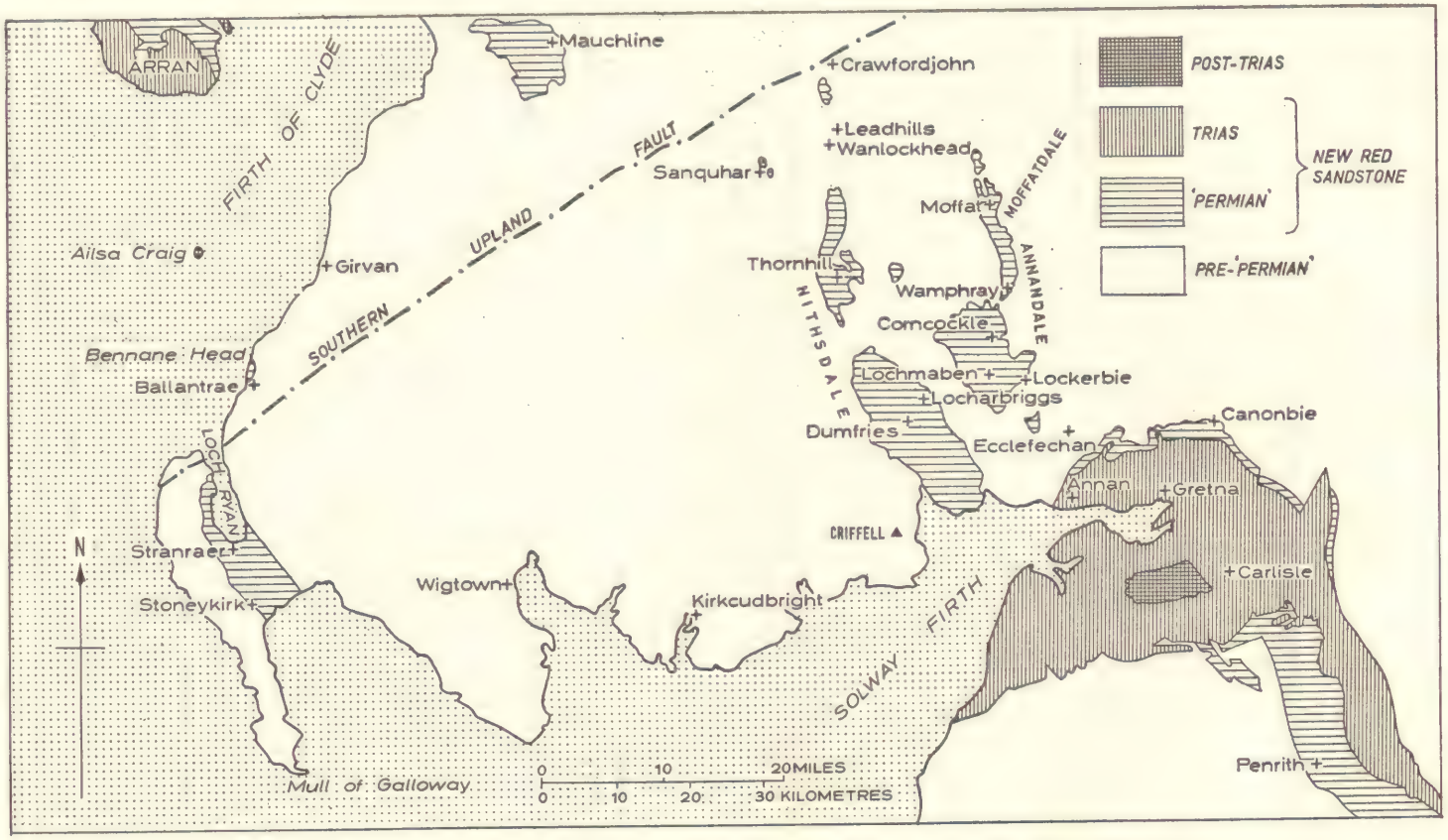

FIG. 16. *Outcrops of the New Red Sandstone in the South of Scotland and the Carlisle Basin*

of olivine-basalt and some of Carboniferous sediment. The Carboniferous rocks near Sanquhar are also cut by thin sills of teschenitic and camptonitic dolerite, and dykes of monchiquite and camptonitic dolerite with a north-westerly trend occur here and elsewhere in the Southern Uplands. A monchiquite dyke in Lauderdale has been considered to be of Carboniferous age on the basis of its pre-'Permian' north-easterly trend, but its petrographic affinities are with the 'Permian' monchiquites of Ayrshire. North-westerly dykes of theralitic essexite near Crawfordjohn and Wanlockhead are assigned to the 'Permian'.

The Snar valley outlier, some four square kilometres in area, lies about 6 km north of Leadhills, and consists of coarse breccias occupying a depression in Ordovician rocks. The rock consists of angular and sub-angular fragments of greywacke and chert, of local provenance, of which the largest are as much as 0·6 m across.

In the Thornhill basin the 'Permian' rocks rest unconformably on both the Lower and Upper Carboniferous. The basal beds are olivine-basalt lavas, probably no more than about 45 m thick, with an underlying thin conglomeratic sandstone or breccia wherever the base of the lavas is exposed. The sandstones and breccias below and within the basalts include angular fragments of greywacke, and lack the brick-red colour and the rounded grains which indicate the arid aeolian conditions of deposition of the succeeding sandstones. South of the latitude of Thornhill these sandstones overlap the underlying lavas to rest directly on the Carboniferous rocks. The lowest beds in the north of the basin often contain angular fragments of basalt, as well as of sandstone and greywacke, which may be polished and faceted after the manner of 'dreikanters'. Occasional large blocks of basalt in higher sandstones demonstrate the irregularity of the lava surface, and show that it remained exposed in places long after the process of burial began. These false-bedded sandstones were formerly extensively quarried at Gatelawbridge, near Thornhill.

The 'Permian' rocks of the Dumfries area generally dip gently to the south-west and consist entirely of red sandstones and breccias. The false-bedded sandstones have been extensively quarried for building-stone, particularly in the vicinity of Locharbriggs, and are known as the Dumfries Sandstones. They rest unconformably on Lower Palaeozoic and Carboniferous rocks and in the south-west they abut against the Criffell Granite. The breccias, which included faceted pebbles of greywacke and granite, appear to occur in the higher beds, cropping out in the south-west of the basin.

The Lochmaben basin also is occupied by red sandstones and breccias. At the extensive old quarries of Corncockle Muir the sandstones are traversed locally by thin veins of pyrolusite, and are noted for reptilian footprints on bedding planes on account of which, over 100 years ago, the rocks were assigned to the Permian. More recently the validity of correlation by footprints has been questioned.

Borings for water have proved the sandstones and breccias to be at least 200 m thick near Dumfries and 90 m, with little breccia, near Lochmaben. The maximum depth of both basins has been estimated by gravity survey to be at least 1000 m, the deepest areas being at Dumfries itself and some 6 km north-north-west of Lochmaben, and there is every indication that the

Dumfries basin, like that of Lochmaben, closes southwards and has no physical connexion with the Permian of Cumberland. The distribution of breccia and sandstone in the Dumfries basin suggests that the basin was already deformed before the breccia was deposited. The gravity information from Stranraer, Dumfries, and Lochmaben presents a consistent pattern of deposition in separate basins which were being actively deepened as sedimentation proceeded, and refutes the older ideas that the 'Permian' rocks are either the remnants of a once continuous sheet preserved by post-'Permian' warping, or the deposits of a 'Permian' valley system draining into the Solway Firth. Additional evidence of 'Permian' tectonic activity is afforded by the restriction of the volcanic necks of this age near Sanquhar to a relatively narrow zone aligned north-westward.

In the upper part of Annandale, north of Wamphray, breccias and red sandstones form a narrow outcrop and rest unconformably on Silurian rocks. The breccias in Moffatdale contain pebbles of fossiliferous Carboniferous rocks.

The Annan Series, which occupies the area between Annan, Gretna, and Canonbie, is considered to be largely of **Triassic** age. The rocks consist mainly of regularly bedded micaceous sandstones, shales, and marls, and lack the dune-bedding, and wind-rounding and polishing of grains and pebbles, which are characteristic of the 'Permian'. Ripple-marking of the marls and the occurrence of possible erosion channels are additional indications of their having been deposited in water. Pebbles of Palaeozoic rock have been found only in the basal conglomerate. Fossils are rare, but footprints of *Labyrinthodon* have been recorded from sandstones near Annan.

The rocks are poorly exposed and have been little studied. In 1916 Horne and Gregory subdivided them, and in 1942 Barrett re-interpreted the succession and correlated it with the Cumberland rocks. The table below shows the essential features of these classifications.

Horne and Gregory		Barrett
		Kirklinton Sandstone
Irregular sandstones with shales	Warmanbie Sandstone	St. Bees Sandstone
Regular red sandstones with shales and erosion channels	Annanlea Sandstone	
Gritty sandstone	Woodhouse Tower Sandstone	Transition beds
Well bedded 'typical Triassic' red marls, with traces of gypsum near the base and ripple-marked shales near the top	Robgill Marls	St. Bees Shales
Massive red sandstone, often soft, and shales	Allerbeck and Cadgill Sandstone	

Barrett discounted the Allerbeck and Cadgill Sandstone as a stratigraphical unit, and assigned the occurrences severally to the transition beds, the St. Bees Sandstone, or to the Kirklinton Sandstone. This last is characterized by the scattered occurrence of bands of wind-rounded quartz grains, and by the absence of the shale bands which split up the St. Bees Sandstone. Barrett also recognized the local development of a thin basal conglomerate with

rounded and angular Carboniferous pebbles. The recent resurvey of the Langholm area by the Geological Survey raises doubt concerning some of Barrett's detailed correlations and the validity of his general classification.

The Annan Series rests unconformably on the Carboniferous and most of its outcrop is made up of St. Bees Sandstone, formerly quarried at Corsehill, near Annan, and elsewhere. The St. Bees Shales lie along the northern margin, in an outcrop which widens from the River Annan, where they are overlapped by the Sandstone, towards Canonbie. The Kirklinton Sandstone, resting locally on a small Carboniferous inlier, occupies a small area around Gretna. The thicknesses of the formations are difficult to assess, and the only estimate to which any value has been attached, even by its author, is a figure of about 120 m for the maximum of the St. Bees Shales.

The boundary between the Permian and the Triassic may properly lie within the St. Bees Shales, their basal beds having a Permian character and their stratigraphy in the north of England suggesting a correlation, in part, with the Middle or Upper Permian marls east of the Pennines. The difficulty of delineating the Permo-Triassic boundary here and elsewhere in Britain has engendered the widely held opinion that the two formations should be combined as the New Red Sandstone.

9. TERTIARY

No sedimentary rocks representative of the time between the Triassic and the Pleistocene occur in the South of Scotland. Nevertheless it is probable that Rhaetic and early Jurassic sediments were deposited in the region, at least as extensively as the Permian and Triassic rocks which now remain, and that in the Upper Cretaceous the Chalk was laid down over most of the region. Eocene basalt lavas, extensively developed in Antrim, may have spread over part of the area.

The only rocks of the Triassic–Pleistocene interval now present are basic Tertiary dykes, which cross the region in a direction which alters gradually from south-eastward to east-south-eastward as the outcrops are followed towards the south-east. They are members of the Mull Swarm and consist either of tholeiite or, rarely, of crinanite (olivine-analcime-dolerite). Several individual dykes can be followed for many kilometres, but there is an element of doubt about some cases of postulated continuity. The Eskdalemuir dyke can be followed from the southern end of the 'Permian' outlier in the Snar valley to Moffat and the vicinity of Langholm. It is of tholeiitic composition and has a width of up to 55 m. This dyke, as well as two other broad dykes within 8 km to the north-east, appears to cross the Southern Upland Fault without displacement. The most northerly of this group is the Acklington dyke, which can be followed from west of Hawick to the coast of Northumberland. The Cleveland dyke of northern Yorkshire may be linked by alignment with the Caponcraig–Coylton dyke of Ayrshire. Between Ayrshire and Cumberland there are two small outcrops of the dyke, at Troston Hill, west of Moniaive, and east of the mouth of the Nith. A branch of this dyke is believed by A. G. MacGregor to follow the Southern Upland Fault east of New Cumnock, and to swing south-eastwards along the boundary fault of the Sanquhar Coalfield. The same author has drawn attention to the similar displacement of another Tertiary dyke a few kilometres to the south-west. Other Tertiary dykes are to be seen on the shore between Girvan and Ballantrae, cutting Arenig volcanic rocks and Silurian and 'Permian' sediments.

The dykes were regarded by Geikie as the fillings of the fissures from which were extruded the plateau basalts, widely developed in the Inner Hebrides and Northern Ireland, but it is now recognized that eruption was from a number of volcanic centres, as propounded by Judd. The dykes radiate from these centres but belong to a later phase of activity than the extrusion of the lavas.

10. PLEISTOCENE AND POST-GLACIAL

The Pleistocene Period, which is defined as extending from the end of the Tertiary Era some 2 or 3 million years ago to the beginning of the Post-Glacial Period about 10 300 years ago, was a period of very marked climatic variation. On several occasions during the period large parts of the Northern Hemisphere were subjected to the most rigorous arctic conditions and, at such times, the south of Scotland was completely submerged beneath exceedingly thick ice-sheets whose outer margins lay far to the south in England. During the interglacials, the periods intervening between successive glaciations, the climate was at times considerably warmer than it is in this country at present, since fossil evidence shows that heat-loving animals such as elephant, hippopotamus and cave-lion existed at these times in parts of southern England.

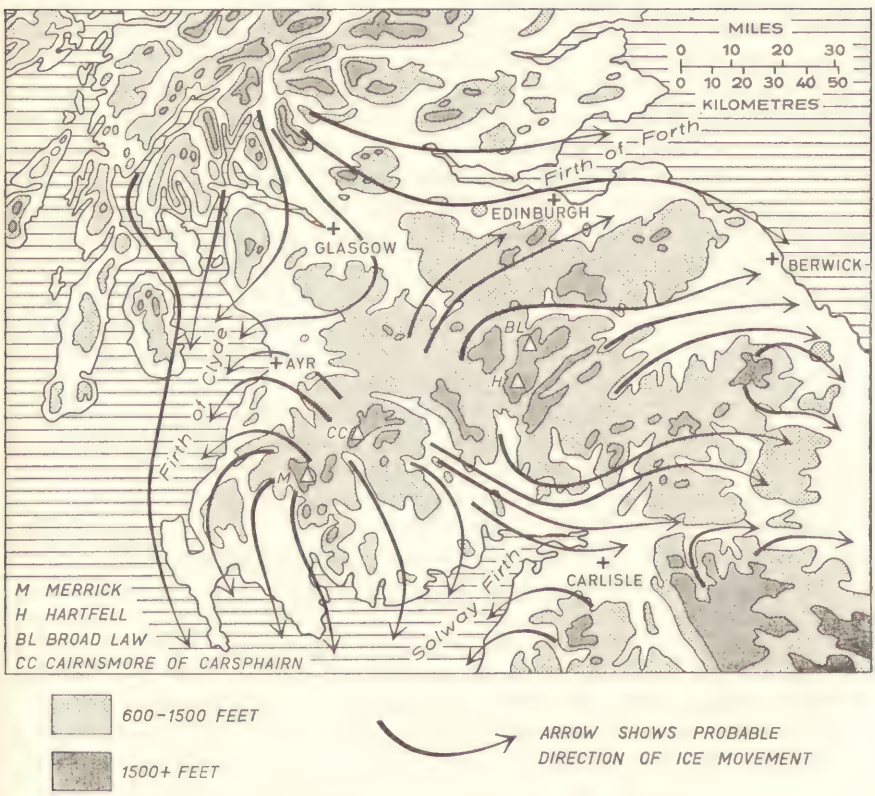

FIG. 17. *Suggested directions of ice-movement over southern Scotland*

Successive glaciations in Scotland probably followed a fairly standard pattern of development. Snow and ice accumulating in the Grampian Highlands and in the higher parts of the Southern Uplands formed valley glaciers which, after expanding to form local ice-sheets, flowed out from the dispersal areas and finally coalesced to form one large ice-sheet.

The dispersal areas in the South of Scotland appear to have been mainly in the high ground around the Merrick, Rhinns of Kells, and Cairnsmore of Carsphairn in Galloway, and farther north-east in the Broad Law, Hart Fell, White Coomb area where the Rivers Tweed, Annan and Clyde now rise (Fig. 17). Ice flowing northwards from these areas met ice emanating from the Grampian Highlands and the two sheets moved off as composite streams towards the lower ground of the east and west coasts. Ice moving southwards from the Southern Uplands became part of the general stream invading northern England. This pattern is confirmed by the evidence from stones carried by the ice, and by striae, the scratches made on the underlying rocks by the movement of the ice.

Later glaciations however, are liable to conceal or to remove the traces of earlier ice-sheets and there is, as yet, no undoubted evidence in the South of Scotland of the Pleistocene events which preceded the latest, or Würm-Weichsel glacial period. This glacial period, which is estimated to have lasted for some 70 000 years and is believed to have included a number of warmer spells, terminated some 10 300 years ago (Fig. 18).

The earliest Weichselian deposits in the region are tills or boulder clays, the ground-moraine of the ice-sheet, consisting of stones and boulders set with no apparent arrangement in an unstratified clayey or sandy matrix. These tills vary in colour and in composition from place to place but are often clearly related to the nature of the underlying solid rocks, indicating that a large part of their materials has not been carried very far prior to deposition. Thus, when the underlying rocks are of Ordovician or Silurian age the matrix of the till is usually brownish grey and the stones are mainly greywackes and hard shales; in areas where the solid rocks are of Old Red Sandstone or Permian age, the till matrix is red and sandy and encloses numerous blocks and boulders of red sandstone; whilst in Carboniferous areas the matrix tends to be grey and clayey, the dominant stones being brown and yellow sandstones, grey shales and Carboniferous igneous rocks. In addition to local constituents the tills also enclose a proportion of far-travelled stones which, if their source is known, can help to determine the direction of ice-movement. In some areas, particularly towards the dispersal centres, the till is replaced by morainic debris consisting largely of local stones and rubble with a sparse, rather coarse-grained matrix.

In general the till tends to be thickest in the valleys and to thin out against the higher ground, suggesting that the topography prior to the Weichselian glaciation must have been very similar to the present form of the ground. There is some doubt as to when this topography was initiated and developed but that it is of considerable antiquity is shown by the form of a channel buried beneath boulder clay in the valley of the River Nith near Sanquhar.

On the lower ground, the upper surface of the till was sometimes moulded by the movement of the ice into long, low hog-backed ridges, known as drumlins, whose longer axes are directed parallel to the direction of flow of the ice. Conspicuous examples occur on the Machars of Wigtownshire

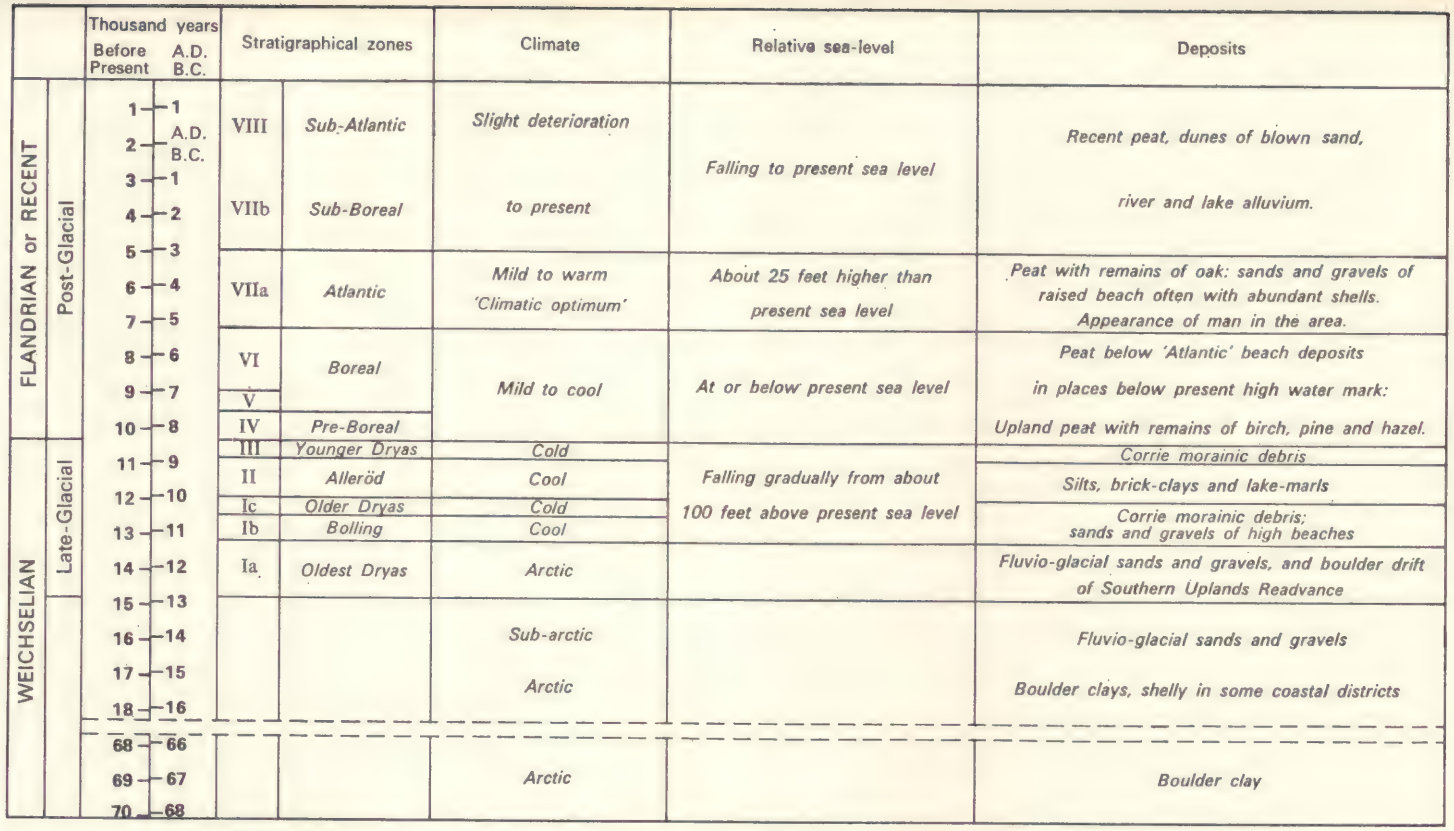

FIG. 18. *The chronology of Late-Glacial and Post-Glacial time in the South of Scotland*

between Burrow Head and Kirkcowan, and the variation in direction of their long axes has been cited as evidence in favour of two different stages of ice-flow over this area.

There are throughout the South of Scotland numerous records of two or more superincumbent tills of very different appearance and composition but there is, so far, no clear evidence to indicate whether these are deposits of different phases of the last glaciation or whether the lower tills are relics of earlier glaciations.

The till, by its very nature, does not normally contain contemporaneou fossils. Along the coast of Ayrshire however, and on the shores of Loch Ryan and the western seaboard of the Rhins of Galloway, a boulder clay is found which contains remains of sea shells evidently picked up from the sea-floor by a stream of ice flowing southwards in the Firth of Clyde.

The erosive power of the ice that carried the till is demonstrated by rock-basins or hollows eroded into solid rock and overdeepened. Loch Doon, Loch Trool and St. Mary's Loch occupy basins of this kind as also do many of the small lochans on the higher ground. Hanging valleys—tributaries joining the main valley at discordant heights—also testify to the powers of glacial erosion. In a striking example situated 14 km north-east of Moffat, the Tail Burn issues from a hanging valley and cascades over the picturesque Grey Mare's Tail waterfall to the floor of the main valley some 100 m below.

As the climate ameliorated some 18–15 000 years ago (Fig. 18), the ice-margin, which at its maximum Weichselian extent lay across England from Yorkshire to Wales, retreated to a position in Scotland to the north of the Southern Uplands, although the uplands at this stage probably nourished a remnant of ice as a local ice-sheet. The climate again deteriorated about 15 000 years ago and the South of Scotland once more became a dispersal area for ice which streamed out to the south over the Carlisle Plain, where it is known as the Scottish Readvance, and probably contemporaneously flowed out to the north as the Southern Upland Readvance into the Midland Valley where its northern margin has been noted in the neighbourhood of Edinburgh.

The retreat of the margin of the southward extension of the ice has been studied in some detail and successive halt or slight readvance stages in the area west of Nithsdale have been named the Monreith, Kirkcowan, Newton Stewart, Minnoch and Corrie stages, the final stages being represented by morainic debris occurring high in the dispersal areas.

Much of the evidence of the retreat of the northward flowing ice lies outwith the South of Scotland region but melt-water channels have been studied in Peeblesshire.

PLATE XI

A. Burnswark, Dumfriesshire. North-westward view near Ecclefechan. In the middle distance is Burnswark, part of a prominent escarpment formed by the Birrenswark Lavas at the base of the Carboniferous.

B. The Eildon Hills near Melrose, Roxburghshire, from the east. The hills are the denuded remains of a composite laccolith of trachytic rocks intruded into the Upper Old Red Sandstone in Carboniferous times.

(*Both photographs reproduced by courtesy of the Committee for Aerial Photography, University of Cambridge.*)

A

B

PLATE XII

A

B

Deposits left during decay of the eastwards extension of the ice in the Tweed Valley are conspicuous, and the later stages in the high ground near the source of the Tweed have been the subject of recent study.

During the retreat phases the increasing warmth released large quantities of melt-water and extensive spreads of water-laid, fluvioglacial materials were deposited. Outwash of this kind, consisting mainly of sand and gravel with well-marked stratification and current-bedding, occurs in the valleys of all the main rivers now draining from the former dispersal areas, the deposits in the Nith, Annan, and Tweed valleys being particularly extensive. Where the ice-margin halted, due to temporary equilibrium between wastage of ice by melting and the renewal of ice from the source, considerable accumulations were deposited (Plate XIIB), as on the isthmus connecting the peninsula of the Rhins of Galloway to the mainland. Deposits of this type were sometimes laid over and around detached masses of ice, the subsequent melting of which resulted in characteristic moundy topography of kame or 'kettle-moraine' type as at Eddleston, Peeblesshire. Deposits marking the former positions of the lateral margins of the ice and of former englacial or subglacial stream courses are also common, conspicuous examples occurring in Berwickshire between Greenlaw and Duns.

During the retreat of the ice-margin, the natural drainage was gradually re-established, but in the early stages it was in many cases obstructed or diverted so that numerous channels, probably excavated by marginal or sub-glacial streams, are found in many areas.

The latter part of the Weichselian, from about 15 000 years ago, has been named 'Late-Glacial' and is subdivided into three zones of which the first and third were arctic and the second, known as 'Alleröd', was much milder climatically (Fig. 18). The Southern Upland Readvance probably took place during Zone I times. Deposits of Zone II (Alleröd) age have been recorded from Whitrigbog, Berwickshire, and some of the higher corrie moraines were probably formed during Zone III times.

The Post-Glacial Period starts from the end of Zone III and a large part of the evidence for the events of the ensuing 10 000 years comes from the peat mosses which may attain a thickness of nearly 6 m in places but are now decaying, particularly in the upland areas. Peat mosses occupy large areas on the lower ground bordering the Solway Firth but are of no great extent in the eastern counties of the region. Elucidated first by macroscopic plant remains, later by pollen-analysis and more recently by radiocarbon dating, the climatic history of the Post-Glacial in this area may be generalized as cold to mild (Pre-Boreal to Boreal), mild to warm (Atlantic), followed by slight deterioration to the present.

PLATE XII

A. Dissected raised beach platform south of Dunbar, East Lothian. Platform of lower (Atlantic) raised beach cut in sandstone of the Lower Limestone Group, Carboniferous Limestone Series, and subsequently dissected by the sea. (Geol. Surv. Photo. No. D1144).

B. The Kaims, near Greenlaw in Berwickshire, are a well-defined kame-moraine of sands and gravels, a deposit formed by glacial streams at the ice-margin. They are also known in literature as the 'Bedshiel Kames'.
(*Reproduced by courtesy of the Committee for Aerial Photography, University of Cambridge.*)

Southern Scotland is believed to have been depressed by hundreds of metres by the weight of ice during the Weichselian, and after its close the land gradually recovered. At the same time world-wide sea-level rose at an irregular rate as the ice-caps melted. The combination of the upward isostatic rise of the land, which was not everywhere at the same rate, and the upward eustatic rise of the sea, caused the relative sea-level around the coasts of Scotland to vary considerably during Late- and Post-Glacial times. Peat beds formed subaerially and now occurring at levels below high water mark at Girvan and along the Solway coast provide evidence of former low sea-levels. Sea-levels higher than at present are recorded by beaches and wave-cut benches from 5 to 9 m above Ordnance Datum, with old sea-cliffs along their landward margins in places. Because of rapid fluctuations the sea-levels indicated in Fig. 18 should be considered only as very broad generalizations. Thus, a subaerial peat, now lying only 4 m above present sea-level near the mouth of the River Cree has been radiocarbon-dated as having formed 6159 years before present, that is, in the middle of the Atlantic or so-called 25-foot beach stage.

The eastern seaboard south of Cockburnspath is predominantly rocky and shows little evidence of these changes in sea-level although recent work suggests that terraces at Eyemouth may have been formed or modified by marine action in Late- or Post-Glacial times. North of Cockburnspath, however, the Atlantic beach is almost continuous as far as Dunbar (Plate XIIA).

On the coasts of southern Ayrshire and Wigtownshire and along the Solway Firth the higher beaches are not clearly marked and in places may be confused with fluvioglacial features. The lower raised beach is however very conspicuous, consisting of a deposit of shingle and sand with numerous littoral marine shells and forming a broad platform the inner margin of which is sometimes marked by low cliff features into which caves have been excavated. Terraces probably related to these changes in sea-level occur along the courses of all the rivers and major streams.

Accumulations of blown sand are small except in Wigtownshire where they form an extensive area of dunes at the head of Luce Bay.

Fresh-water alluvium forms low terraces fringing most of the rivers and also occurs as flat expanses marking the sites of many former lakes.

Evidence for the presence of early man in the region, probably during Atlantic times, is provided by Mesolithic flint implements which have been found at Stoneykirk near Stranraer in Wigtownshire and at a site near the confluence of the rivers Ettrick and Tweed in Selkirkshire.

11. ECONOMIC GEOLOGY

The principal mineral products of the South of Scotland are those used in the construction industries, such as building stone, sand and gravel, and roadstone. Of more localized importance are limestone, monumental stone, coal, and clay and shale. The water resources of the region are widely, but by no means fully, exploited. Until very recently metalliferous mining was from time to time locally of great importance, but at present there is little activity in this field.

Granite

The granodiorite of Criffell and a small granite mass south of Creetown are quarried, the former near Dalbeattie, for monumental stone, building-stone, and aggregate. Synthetic stone and concrete products are also made from the crushed rock. Plans were announced in 1965 for the quarrying of road-stone in the Cockburn Law Granite in Berwickshire. The building stone is used mainly in such projects as bridges, docks, and public buildings. Other important products of the quarries are road chippings and setts.

Basalt, Dolerite, and Porphyrite

Basalt lavas of Lower Carboniferous age, and the rocks of a variety of minor intrusions, are widely quarried and crushed for use as roadstone and concrete-aggregate. The basalts are mainly in Roxburghshire and Berwick-shire, porphyrite is quarried near Kirkcudbright, and the other minor intrus-ions are worked at localities scattered throughout the region. In Dumfries-shire the basic rock of the Tertiary Eskdalemuir dyke was quarried recently near the Black Esk Reservoir, to be used in its construction both as building stone and as aggregate. It is at present quarried near Moffat.

Sandstone and Greywacke

The towns of the South of Scotland were generally built of local stone, of which the most commonly used were Lower Palaeozoic greywacke, Carboni-ferous sandstone, and 'Permian' sandstone. Sandstone near the base of the Carboniferous has been much quarried at Langholm and at Swinton in Berwickshire, and north-east of Kelso the dolomitic Carham Stone has been much used for building as well as being burnt for lime. The Carboniferous or Permian red sandstones of Dumfriesshire have been extensively used for building, both locally and in the Midland Valley, the principal quarries being near Dumfries, where work continues at Locharbriggs, and near Lochmaben. The stone is also used for monumental work, and the waste sand for making sand-lime bricks. In the Annan district red sandstone of Triassic age is the principal building stone.

Greywacke is much used today as a source of roadstone, and quarries, disused and operative, are scattered widely over the Lower Palaeozoic

outcrop. Contact-altered greywacke is, or has been, quarried near Kirkgunzeon in Kirkcudbrightshire, at Clatteringshaws, west of New Galloway, in the porphyrite quarry (see above) near Kirkcudbright, and near Moffat.

Limestone and Dolomite

Near Girvan Ordovician limestone is quarried at Craighead and at Tormitchell, and other limestones of this age, associated with volcanic rocks, were formerly worked in the Tweed Valley near Peebles. Limestones in the Lower Carboniferous are worked near Dunbar and in Dumfriesshire, near Ecclefechan and near Canonbie. There are old workings in the Lower Carboniferous in Liddesdale above Newcastleton, near Kelso (Carham Stone), and near Annan. The rock formerly mined at Barjarg, near Thornhill, is a dolomite of considerable purity. The principal uses to which the limestone is put are in cement manufacture in the important works near Dunbar and as fertilizer and roadstone.

Clay and Shale

The only active workings of clay in the region are near Newton Stewart, where raised beach clays are used to make agricultural drain tiles, and near Langholm, where the material is derived from a small glacial pond deposit. Old tile works are known to occur at several localities, and suitable deposits of lacustrine clay or boulder clay are probably available at some of these and elsewhere if required.

Lower Palaeozoic shales were formerly quarried at Cairnryan, near Elvanfoot, and near Stobo and Innerleithen, for use as roofing slates. Near Stoneykirk in Wigtownshire, where toughened by an igneous intrusion, they are used as roadstone.

Sand and Gravel

Pits in superficial sands and gravels are scattered throughout the populated parts of the region, with a certain concentration around Stranraer, in lower Nithsdale and Annandale, and in northern Peeblesshire. The sand is used mainly in the building trade, for mortar, plaster, sand-lime bricks, and other similar purposes. Most of the gravel is used to make concrete and in road construction. Other uses of sand are in water filtration, horticulture, iron- and steel-moulding, and glass-making.

Peat

Hand-cutting of peat for local use as fuel has been widely practised in southern Scotland since ancient times. Mechanical techniques were introduced at Lochar Moss, near Dumfries, in 1910, for the manufacture of ammonium sulphate and peat briquettes, and exploitation continued until the Second World War. The Scottish Peat Committee, appointed by the Government, reported in 1962 that at that time peat was a more costly source of energy than other available fuels, and that in the immediate future the main value of the peat-mosses would appear to lie in the cultivation of farm crops and trees and in the use of processed peat in horticulture.

Coal

At present the only working collieries in the region are at Kirkconnel, in the Sanquhar basin. Considerable reserves of unworked coal have been proved to the south of the old coalfield at Canonbie. Coal was also formerly worked in Liddesdale for local use as fuel.

Iron and Manganese

Veins of hematite were worked in the last century at the edge of the Loch Doon Granite south-east of Loch Doon, and in the Criffell Granite east of Kirkcudbright. Hematite also occurs at Wanlockhead and Leadhills, in association with the lead-zinc veins. Near Lamancha in Peeblesshire a concentration of hematite, in red shales and cherts overlying Arenig lavas, was mined in the 1880's. A band 0·45 m thick, some 1·5 m above the hematite, is rich in pyrolusite. The beds are closely folded and other outcrops of the ores may occur nearby.

Copper

During the 19th century, and in the years just before and after, there were several small copper mines and trials in the South of Scotland. The usual ores are chalcopyrite and malachite, often in veins of crushed rock with calcite and quartz as the main gangue minerals. There were mines near Girvan, Whithorn, and Kirkcowan, on the coast south-east of Castle Douglas, and in the Priestlaw Granite in East Lothian. The ores were also won in the lead-zinc areas of Leadhills and between Newton Stewart and Gatehouse of Fleet. There are old trial mines near Moffat, and near Lauder and Abbey St. Bathans in Berwickshire.

Lead and Zinc

Galena has been mined at Leadhills and Wanlockhead for at least 700 years, and the associated zinc-blende at Wanlockhead from 1880. The ores occur in shoots up to 3·7 m wide in veins of brecciated Ordovician greywacke which dip at about 75 degrees towards the north-north-east, but are poorly developed, if at all, where the brecciated rock is shale or chert. Gangue minerals are mainly quartz and calcite. The mines were closed in 1929 and were reopened for about a year in 1934 and in 1957, but considerable reserves of unmined galena remain. Extraction of ore from the old tips was practised in the middle 1960's.

Both galena and zinc-blende were mined, in the last century, on the south-western flank of the Cairnsmore of Fleet Granite from Gatehouse of Fleet to north-west of Newton Stewart. Most of the veins, which occur in greywackes of Llandovery age, run in a west-north-westerly direction. Other ore-minerals present include chalcopyrite, baryte, and mispickel. There was some revival of mining at the time of the Great War but no sustained activity has taken place since then. Between 1840 and 1873 galena was worked opencast and mined at Woodhead, between the granites of Loch Doon and Cairnsmore of Carsphairn. The veins, cutting Ordovician greywackes, dip to the north-north-east at about 60 degrees. Zinc-blende and chalcopyrite are also present.

Lead and zinc have also been worked near New Luce, near Barr in Ayrshire, and near Traquair.

Silver and Gold

Prior to the 17th century silver was probably the main product of the galena mining at Leadhills. More recently it was obtained as a by-product of the treatment of galena at Leadhills, Wanlockhead, and Blackcraig, near Newton Stewart.

Alluvial gold was won in the 16th century from Glengaber Burn, near St. Mary's Loch, and at Leadhills. A small vein of gold-bearing quartz was reported from the latter area.

Antimony

Some of the galena veins of Leadhills contain jamesonite, a sulphantimonide of lead, but the main source of antimony in the region has been the Glendinning Mine, north of the road from Langholm to Eskdalemuir, where stibnite occurs in a vein 0·45m wide in a breccia of Wenlock shale which dips at upwards of 80 degrees to the south-east. Ore-minerals include galena, jamesonite, and zinc-blende. The mine was last operative in 1920. Stibnite has also been mined within a small granite mass at The Knipe, south-east of New Cumnock.

Nickel and Arsenic

Niccolite (nickel arsenide) and mispickel (iron sulpharsenide) occur close together at Talnotry, near Newton Stewart. Old trial workings exist in both ore-bodies, the former apparently a restricted lens, the latter a vein at the margin of the Cairnsmore of Fleet Granite.

Baryte

Veins of baryte occur in the Wenlock and Lower Carboniferous rocks to the south of Auchencairn in Kirkcudbrightshire, and until 1961 the mineral was worked intermittently and on a small scale at several points near the coast. Baryte has been worked, in association with copper ores, in the Priestlaw Granite in East Lothian.

Water

Most water authorities within the region, and several in the Midland Valley, draw upon the ample supplies of surface water of high quality which exist in the Southern Uplands. The Talla and Fruid reservoirs, in the upper part of the Tweed Valley, are important constituents of Edinburgh's supply-system. The 'Permian' sandstones of Dumfries, Lochmaben, Thornhill and Stranraer form the principal underground aquifers, but are heavily exploited only in the Dumfries area where 150 000 litres an hour are pumped from one of the wells. Smaller supplies are obtained from sandstones in the Old Red Sandstone and Carboniferous, and from superficial sands and gravels, and are irregularly present in open joints near the surface in greywacke and granite areas.

Sulphurous and chalybeate springs occur at a number of localities, the most famous being in the Moffat area, where Moffat Well itself has been dismantled but Hartfell Spa is still in use, and St. Ronan's Well at Innerleithen, which is also still used.

12. GEOLOGICAL SURVEY MAPS OF THE SOUTH OF SCOTLAND

(*a*) **On the scale of 4 miles to 1 inch (1/253 440)** Colour-printed.

Sheet 14 Firth of Clyde, North Ayrshire, Lanarkshire.
Sheet 15 Firth of Forth, Peeblesshire, Berwickshire.
Sheet 16 South Ayrshire, Galloway.
Sheet 17 Dumfriesshire, Selkirkshire, Roxburghshire.

(*b*) **On the scale of 1 inch to 1 mile (1/63 360)**

(i) *Hand-coloured Sheets* (*out of print*)

6 (Annan); 10 (Dumfries); 18 (Morebattle); 25 (Kelso); 34 (Eyemouth).

(ii) *Colour-printed Sheets*

These sheets show both 'solid' and 'drift' deposits. Those marked * are printed in separate 'solid' and 'drift' editions.

1 (Kirkmaiden); 2 (Whithorn); 3 (Stranraer); 4 (Wigtown); 5 (Kirkcudbright); 7 (Girvan); 8 (Carrick); 9 (Maxwelltown); 11* (Langholm); 14* (Ayr); 15* (Sanquhar); 16 (Moffat); 17 (Jedburgh); 23* (Hamilton); 24* (Peebles); 33 (Haddington).

(iii) *Colour-printed Provisional Sheet*

26 (Berwick upon Tweed [Duns]).

Memoirs have been published describing the geology of the areas covered by sheets 1, 2, 3, 4, 5, 7, 9, 11, 14, 15, 23, 24, 33 and 34.

(c) On the scale of 6 inches to 1 mile (1/10 560)

The area is also covered by geological maps on the six-inch scale. In general these are not published but may be consulted at the Institute of Geological Sciences, 19 Grange Terrace, Edinburgh EH9 2LF. Uncoloured copies may be supplied on special order.

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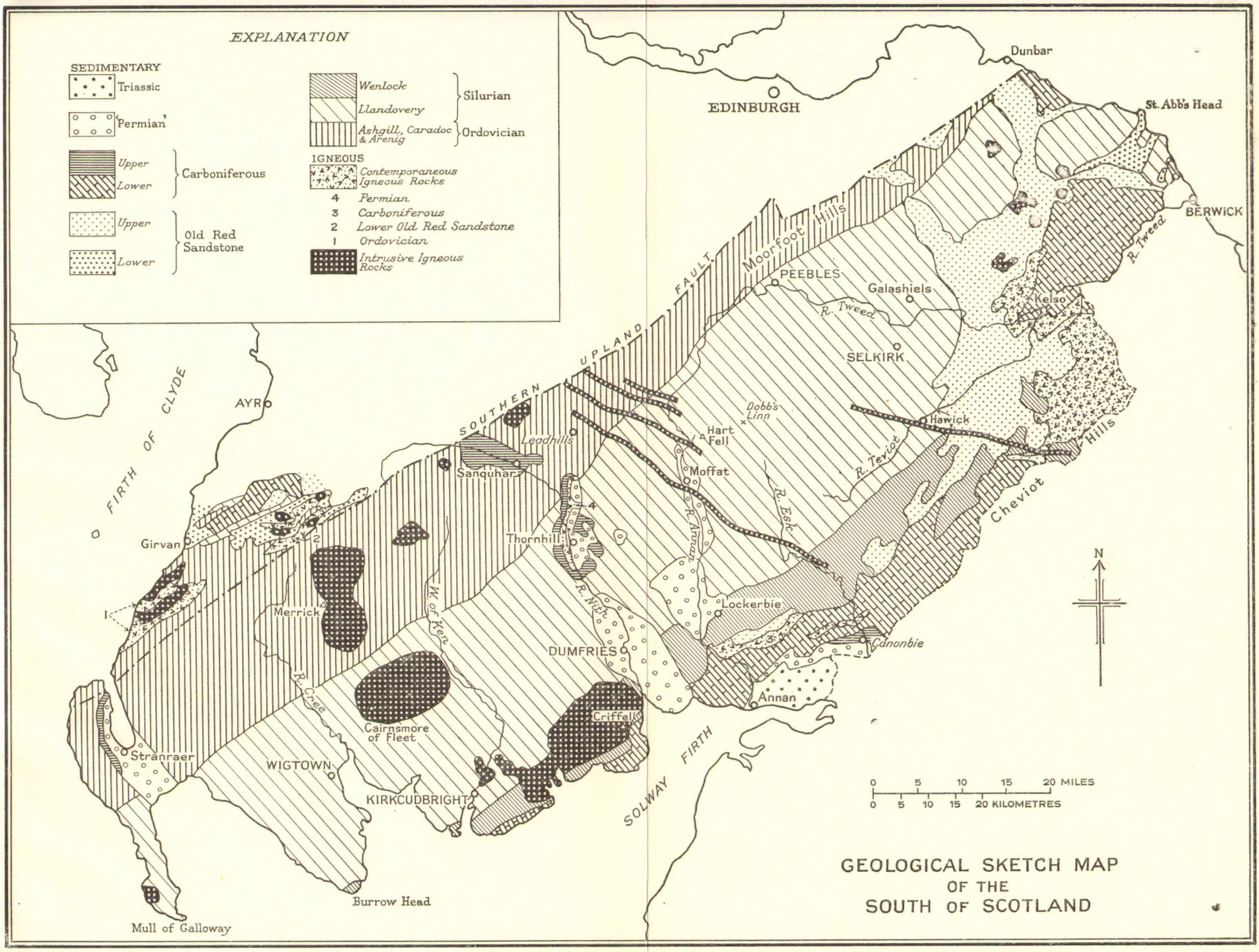

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